PULVERISED AND COLLOIDAL FUEL

J. T. DUNN

Date Due

MAY 27 1980			
FEB 16 1982			

PULVERISED AND COLLOIDAL FUEL

PULVERISED AND COLLOIDAL FUEL

By J. T. DUNN
D.Sc. (Dunelm.), F.I.C.
Consulting Chemist, Newcastle-upon-Tyne

NEW YORK
VAN NOSTRAND COMPANY
EIGHT WARREN STREET
1924

Made and Printed in Great Britain at
The Riverside Press Limited, Edinburgh

PREFACE

The use of powdered fuel has of late greatly increased in America, both in the number and the size of individual plants; and it has made rapid progress in France. We in this country have been relatively slow to adopt it.

The economical use of our fuel supplies is a matter of ever-increasing moment to us, and any method of using fuel that holds out promise of greater economy merits careful consideration at the hands of fuel users. Powdered fuel offers undoubted advantage in many instances, and the author felt that, in acceding to the publishers' request that he should write for this series a book on powdered fuel, he would be making some small contribution towards the conservation and efficient use of our national fuel supplies.

A large part of such a book must consist of descriptions of actual plant, involving engineering details; but the burning of fuel is after all a chemical process, and must be carried out in accordance with chemical principles. The author has endeavoured to present these underlying principles and to give a fair account of the advantages and disadvantages, as they appear to him, accompanying the use of powdered fuel for various purposes. He has made personal acquaintance with a large number of powdered fuel plants, but has naturally also had to make considerable use of published information and of the experience of others. It is of course impossible to enumerate all these sources of information, but he wishes here to acknowledge his indebtedness and offer his thanks to all who have so generously helped him: to the Controller of His Majesty's Stationery Office for the use of portions of Mr Harvey's report to the Fuel Research Board on Powdered Fuel Systems in America, and to Messrs Constable for similar use of Mr Herington's book on *Powdered Coal as a Fuel*. He has also derived great help from a report by Mr Blizard to the Canadian Department of Mines; from a pamphlet by P. Frion, reprinted from *Chaleur et Industrie*; from a short treatise by F. Münziger on *Powdered Coal for Steam Boilers*; and from three very valuable papers in the *Proceedings of the Engineers' Society of Pennslyvania*, a general

paper by Mr Muhlfeld, one by Mr Tracy on *Explosion Hazards*, and one by Messrs Kreisinger and Blizard on *Tests of a Steam Plant.* He has also derived much information, naturally, from some of the prominent firms manufacturing plant for powdered fuel: the Powdered Fuel Plant Company, the Fuller Engineering Company, the Raymond Bros. Engineering Company, the Sturtevant Engineering Company, the Underfeed Stoker Company, Messrs Simon-Carvés, and others; from many users of powdered fuel, who have kindly allowed him to inspect in detail their installations at work; and in the matter of colloidal fuel from Mr Lindon W. Bates.

The book is primarily an exposition of principles and does not pretend to describe every form of plant on the market for preparing or utilising powdered coal. Typical forms are mentioned, but it must not be inferred that there are not other makes which are efficient and useful.

J. T. D.

Newcastle-upon-Tyne,
November, 1923.

CONTENTS

LIST OF ILLUSTRATIONS

PART I

PULVERISED FUEL

INTRODUCTORY

For almost all industrial purposes mechanical power is needed. In the early stages of civilisation this was always derived from the muscular exertion of man or animals; but to-day, though for certain operations this is still made use of, and no substitute for it can be found, yet the amount so derived is but a minute and almost negligible fraction of the total amount of power in use.

In this country the source of practically the whole of the enormous amount of power which industry requires is the energy yielded by the combustion of fuel. Sporadic installations exist, which derive their power from the energy of waterfalls, of tidal flow, or of winds; but these are few, and form an insignificant portion of the total.

Apart from power, many industries need heat to be developed, either because they depend on the carrying out of chemical reactions which will only occur at high temperatures, or because a high temperature is needed to modify the physical characters of the substances they deal with, in such a way as to make them amenable to the purposes of the industry. The production of iron from its ores, or of steel from iron, for example; the production of glass, and many similar industries, all involve reactions that will only take place at high temperatures; whilst the operations of the foundry, the forging of heated steel, and the various alterations in the hardness and other qualities of metals produced by heat treatment are other examples of the same need of high temperature. The heat required for these operations, like that required for the development of power, is all obtained by the burning of fuel.

All chemical reactions involve not only changes in the form and in the composition of matter, but energy changes also; and in general it may be said that when two substances combine chemically, energy (usually in the form of heat) is set free, and when a substance is decomposed energy

is absorbed. Any substance capable of entering into chemical reaction with another and of evolving heat which can be utilised as a source of power or of high temperature might be spoken of as fuel; but in practice the number of such substances obtainable in sufficient quantity and at sufficiently low cost to be actually used for the purpose is very limited. The natural fuels are such substances as wood, lignite, peat, coal, mineral oils, natural gas; and all other fuels are derived from these, especially from the solid fuels, by treating them in some way—charcoal, coke, shale oils, tar and tar oils, alcohol, benzene, coal gas, water gas, producer gas, blast furnace gas.

All of these fuels have been originally produced from living matter, and they all contain the elements found in organised bodies—carbon, hydrogen, oxygen, nitrogen and sulphur, with in most cases a certain percentage of mineral matter, which, when the fuel is burnt, is left behind as ash. The essential heat-giving elements of the fuel are carbon and hydrogen, and the combustion of the fuel consists essentially in the combination of the carbon and the hydrogen with the oxygen of the air, to form carbon dioxide and water respectively.

The general principles which underlie the use of any fuel are very simple and easily understood. A definite amount of any fuel will yield by its combustion a definite amount of heat; for example, 1 kilogram (or 1 lb.) of coke or charcoal will give out, in burning completely, about 8000 heat units—as much heat as would raise 8000 kilos. (or lbs., as the case may be) of water through 1° C., or would do any equivalent amount of heating. We cannot get more than this, nor will any less be evolved if the combustion be complete, though we may, by the faulty disposition of our apparatus, uselessly waste some of it, and thus effectively get less. The technical problem which we have to solve in any given instance is so to construct the plant and manage the operation that we shall burn the fuel as nearly completely as possible, and thus obtain all the heat that it can yield, and shall then utilise that heat with as little loss as possible.

The only natural fuel which we in this country possess at the present day is coal. It is true that there are in the country considerable deposits of peat; but the difficulties in the way of its utilisation have so far

prevented it from being used on any large scale as fuel. The Scottish oil shales are very restricted in quantity, and of mineral oil and natural gas we may be said to have, for practical purposes, no supplies.

Our coal resources are being drawn upon at a very rapid rate. During the years 1910-1914 the production in Great Britain averaged 270,000,000 tons per annum, and it had for many years been steadily rising to that figure. The check which industry received through the war and its consequences, and which has been reflected in our coal consumption, will not be permanent, and the consumption will again rise, beyond the pre-war figures. The more accessible and easily worked seams, and those of the best quality, are naturally worked first; many of them are worked out, others are approaching their end. Seams more difficult to work, and of poorer quality, have to take their place, and the supply of coal tends, both in consequence of that and because of the higher cost of labour, to become continually more costly. Economical and efficient use of our coal, therefore, is not merely a desirable thing from the point of view of saving our own pockets and of making our industry a greater pecuniary success. It is a duty we owe to the nation, not to waste its resources, and a duty we owe to posterity, not to deprive them recklessly of their inheritance. Any improvement in the methods of utilising our fuel, which will either, by securing better combustion, yield us more heat from the same fuel, or, by lessening waste of the heat when obtained, enable us effectively to obtain the same amount of heat from a smaller amount of fuel, or which will allow us to use as fuel coals which hitherto it has not been possible to use—any such improvement demands consideration at the hands of all who are concerned in the use of fuel for industrial purposes.

It is claimed for the use of coal in the powdered form that it does effect economies in all of the directions just enumerated: that it stops the waste due to unburnt coal either in soot or in clinker; that it allows furnace arrangements such that less of the heat generated is carried away uselessly than in the ordinary burning of coal on grates; and that it enables us to burn usefully many coals or grades of coal which are now not worth bringing to the surface, or if brought to the surface are rejected as useless for economical burning as fuel.

In examining these claims it is to be borne in mind that the word economy is used in two senses. There is the technical sense, meaning high efficiency: the utilisation of a high percentage of the total heat theoretically obtainable from the fuel; and there is the industrial or commercial sense: the production of the substance or article with which we are concerned at as low a cost, for fuel and for the labour and appliances needed to burn it, as possible. The achievement of these different ends will not necessarily be attained always by the same methods or by using the same means. One fuel may be so much lower in cost than another, for example, that though when we use it we burn it inefficiently and wastefully, it may yet effect its object at a lower cost than the other, although we may be able to utilise that one with a high degree of efficiency. Again, if we are considering the same fuel, it is obviously desirable and truly economical in the technical sense to burn it efficiently rather than inefficiently and wastefully; but if, in order to use it efficiently, we have to make different arrangements from those obtaining in its ordinary inefficient use, whether the new method will be "industrially" economical or not will depend upon whether or not the saving of fuel due to the technical economy more than balances the extra cost of the new arrangements made to burn it. If we can make nine tons of fuel do the work formerly done by ten, or if we can make ten tons of a cheap and inferior fuel do the work of ten tons of a better and more costly fuel, we have in either case effected a real economy, and from the point of view of the conservation of our coal supplies the change is entirely to the good; but if in order to effect this change we have to incur a total cost of a hundred pounds where we formerly paid ninety, the change will not be industrially practicable.

It is not enough, therefore, to show that coal used in the powdered form can be made to burn more nearly completely, and therefore more economically in the technical sense, than when used in lump form on a grate; or that a poor coal, cheaply obtainable, used in powdered form could be made to displace a better and more costly coal, whilst it would be impossible to use the poor coal at all in the ordinary way. It will be necessary, if powdered coal is to substitute the ordinary methods of burning lump coal in grates, that the cost of installing the needful plant and

machinery, and the cost in power and labour of working the new system, shall not be so great as to overbalance the savings to be effected by the increased efficiency of the system; and each individual proposed installation will need separate examination on this account. Mistaken enthusiasm in introducing pulverised fuel without this previous examination has led to many disappointments, and aroused in certain quarters a prejudice against it, just as unreasonable as the enthusiasm which proposed to introduce it everywhere.

COMBUSTION OF COAL IN LUMP AND POWDER

The difference in the conditions under which coal in the lump form and the same coal in the powdered form burn is very great and very striking. Combustion can only occur when the combustible substance and the oxygen of the air are in actual contact with one another; and an inch cube of coal will expose 6 square inches of contact surface. As the coal burns away the surface will of course continually decrease and the rate of combustion gradually slow down. If the coal contain ash, as all coals do, the combustion of the inner layers as the outer ones burn away will be interfered with and its rate still further slowed by the coating of ash, which will impede and render more difficult the access of the necessary air to the coal.

Let us suppose a given coal to contain 80 per cent. of carbon and 5 per cent. of hydrogen. In burning, each 12 parts, by weight, of carbon take up 32 parts of oxygen, forming 44 parts of carbon dioxide; and each 2 parts of hydrogen take 16 of oxygen, forming 18 parts of water or steam. Every 1 lb. of the coal burnt, therefore, will require for

0·8 lb. of carbon,	$\frac{32}{12} \times 0{\cdot}8$,	or 2·13 lbs. of oxygen	
0·05 lb. of hydrogen,	$\frac{16}{2} \times 0{\cdot}05$,	or 0·40 lb.	„
—in all,		2·53 lbs.	„

In every 100 lbs. of air 23 lbs. are oxygen and 77 nitrogen, so that the

2·53 lbs. of oxygen required will be associated with $\frac{77}{23} \times 2{\cdot}53$, or 8·47 lbs. of nitrogen; or 11 lbs. of air will be needed to burn 1 lb. of coal, and as 1 lb. of air occupies, roughly, about 13 cubic feet, 1 lb. of coal will require about 143 cubic feet. If the coal has a specific gravity of 1·3, a cubic inch will weigh 0·048, or say 0·05 lb., and will therefore need for combustion $0{\cdot}05 \times 143$, or say 7 cubic feet of air; a cube 1·92 feet, or rather over 23 inches, in the side. All of this air has to be brought into contact with the 6 square inches (gradually lessening) of burning surface before the coal can be completely burnt.

If this cubic inch of coal be divided into smaller cubes, each of $\frac{1}{100}$ inch in the side, there will be $100 \times 100 \times 100$, or 1,000,000 such little cubes. Each of these will have six surfaces of $\frac{1}{10{,}000}$ square inch in area, so that the whole of them will expose a surface of 600 square inches, or 100 times as great as that of the original cube.

The same 7 cubic feet of air will of course still be needed for combustion; and if we suppose the million little cubes to be evenly distributed through this volume, each particle will be at the centre of a little cube of air of its own, less than a quarter of an inch in the side. It is quite clear that the conditions here are far more favourable to rapid and complete combustion than in the former case, even were the coal completely combustible; still more so when it contains a quantity of ash, which obviously will interfere very much less with the combustion in this finely divided condition than when it forms a thick protective coating over the whole cubic inch of coal.

The comminution of coal in actual working in pulverised fuel installations is usually carried much further than in the supposititious instance above. Usually 95 per cent. of the whole will pass through a sieve with 100 meshes to the linear inch, and 80 per cent. or more through a 200-mesh sieve. The actual aperture in these sieves is only half the linear measurement of the mesh (for the wire occupies half of it); so that the largest particles passing these two sieves would have linear dimensions of $\frac{1}{200}$th and $\frac{1}{400}$th of an inch respectively; and besides these largest particles which only just pass through there are many more which are much smaller

and drop through without touching the wire. We shall be within the mark, then, in assuming that the average particle of such coal is a cube not more than $\frac{1}{400}$th of an inch in the side, or one quarter of the linear dimension, one sixty-fourth of the bulk, of the particles we have just been considering. The conditions with such a powder, evenly distributed through the accompanying air, would be still more favourable to rapid and complete combustion. Each particle would be at the centre of a cube of air only about $\frac{1}{10}$th of an inch in the side, and the aggregate surface exposed would be 4 times 600, or 2400 square inches: over 16 square feet.

There is another circumstance which complicates the problem of burning coal efficiently, which has not to be considered with other fuels, such as coke, oil or gas. This is the fact that coal is a substance readily decomposable by heat, so that when burnt in a furnace it does not burn away as a whole, continuously, but gives off, as it heats up, large volumes of combustible gases or vapours, and leaves behind a solid residue of carbon or coke; that these various substances do not burn with equal readiness; and that the supply of air for combustion has therefore to be so regulated that it can deal with the gaseous as well as the solid products of this decomposition. If the supply of air be short, much of the volatile combustible matter goes off as smoke, causing both loss or waste and nuisance; and to ensure against this a considerable amount of surplus air has in practice to be supplied to the furnace beyond that theoretically sufficient for the combustion. This again involves waste, for the whole of this surplus air, which contributes nothing to the amount of heat evolved, leaves the furnace at a temperature considerably higher than that at which it entered it, and carries off uselessly a corresponding amount of heat.

The combustion of each particle of coal in a cloud of powdered coal and air follows the same chemical process as that of a lump of sensible size; but the dimensions of the space concerned are so small, and the reacting substances, coal and air, are so much closer at hand to one another, that the time interval between incipient decomposition and complete combustion is negligibly small; the whole action takes place almost as though the combustible were a gas: and combustion is complete with practically no surplus air present.

HEAT

No sound knowledge of the process of combustion is possible, and no sound reasoning or judgment on the circumstances attending the efficient use of fuel, without an elementary acquaintance with the facts and laws which govern the production and the communication of heat, and it will be well, therefore, to enter here into some of these matters at some little length.

Heat is measured, as has already been said, by its effect in raising the temperature of a standard substance. Water is chosen as this standard substance. The metric unit of heat, 1 calorie, is the amount of heat which will raise the temperature of 1 kilogram of water through 1° C. The "British Thermal Unit"—B.Th.U.—is the amount which will raise 1 lb. of water through 1° F. A calorie is equivalent to 3·969, or very nearly 4 B.Th.U.

CALORIFIC VALUE

The calorific value of a combustible substance is the number of heat units evolved when unit weight of the substance is completely burnt; it is an expression, therefore, of the number of calories evolved by a kilogram, or the number of B.Th.U. evolved by 1 lb.; and the first figure is convertible to the second by multiplying by 1·8, the ratio of the length of a centigrade to that of a Fahrenheit degree.

The calorific values of a great many combustible substances, both elements and compounds, have been determined with considerable accuracy, and a few of the most important of these are given in the following table (p. 21.) Attention should be directed to one or two points here. First, the calorific value of a compound cannot be obtained by calculation from those of its elements. Methane, for example, is a compound of 12 parts of carbon and 4 parts of hydrogen, by weight. From the table, 12 kilos. of carbon will evolve 96,960, and 4 kilos. of hydrogen 136,800 calories; the sum of these is 233,760 for 16 kilos. of methane, and therefore 14,610 for 1 kilo. But the figure given for methane is far below

this, 13,070 calories. The difference is due to the fact that carbon and hydrogen, in combining to form methane, evolve heat (the reaction is, in fact, exactly the same in nature as a combustion, though we do not think of it as being so because the oxygen of the air is not involved in it); and, in the burning of the methane, before the carbon and hydrogen can separately form compounds with oxygen, this amount of heat has to be supplied to the methane in order to undo the compound and set the carbon and hydrogen free again. With many compounds (methane itself is an example), the only way we have of determining their "heat of formation"—*i.e.* the amount of heat given out when definite weights of their constituents combine—is to find the calorific values of the constituents and of the compound, and take the difference between them (for methane, 1540 calories from the above figures).

TABLE OF CALORIFIC VALUES

	Calories per kilo.	B.Th.U. per lb.	Calories per cub. metre	B.Th.U. per cub. foot
Carbon . .	8,080	14,540	..	..
Carbon (to monoxide)	2,410	4,340	..	..
Hydrogen . .	34,200	61,560	2,854	321
Sulphur . .	2,166	3,900	..	..
Carbon monoxide .	2,430	4,370	2,845	320
Methane . .	13,070	23,530	8,870	998
Ethylene . .	11,640	20,950	14,050	1580

Again, an element sometimes forms two or more compounds with another; thus 12 parts of carbon combine with 16 of oxygen to form carbon monoxide, or with 32 parts of oxygen to form carbon dioxide. It will be seen that whilst 12 kilos. of carbon in burning completely to carbon dioxide give out 96,960 calories, 28 kilos. of carbon monoxide (the amount which contains 12 kilos. of carbon) in burning to carbon dioxide give out 67,480. We might think that by burning carbon in two separate stages, first to monoxide, then to dioxide, we should get twice 67,480, or 134,960, instead of 96,960, and thus effect a most important economy. But then we burn 12 kilos. of carbon to monoxide only, we find that we get

actually an evolution of, not 68,000, but only 28,920 calories, and that the sum of the results of the two-stage operation is exactly the same as that of the single-stage one. The difference is due, partly at least, to the fact that the solid carbon is converted during the combustion into the gaseous form, and that the energy required for this is supplied out of the heat which the combustion evolves. In the second stage the reacting substances and the product are alike gases.

Coal is a very complex mixture of compounds. Though an enormous amount of investigation has been carried out upon it, we know as yet very little of the substances composing it, or of their calorific values, and it follows, too, that we do not know whether coals of different origin contain the same or different constituents. We are not therefore able to calculate with certainty the calorific value of a coal; though if we make an analysis of it, calculate the calorific values of the carbon, hydrogen and sulphur which it contains (deducting from the total amount of hydrogen the amount needed to form water with any oxygen in the coal), and add these together, we get as a rule a fair approximation to the truth. But it is easier, as well as more satisfactory, to determine the calorific value of the coal directly. This is done by burning a weighed portion of the coal completely in compressed oxygen, in an apparatus so arranged that no heat is lost in the operation, or so that if any is lost its amount can be accurately ascertained and allowed for, and measuring the rise of temperature of a known amount of water, into which the heat yielded by the combustion goes. The principle of the operation is extremely simple and easily understood, although to carry it out much care, skill and attention to details are needed.

In the case of gaseous fuels, where the amount dealt with is always expressed as a volume, and only very rarely and for special purposes as a weight, the calorific value is usually given as calories per cubic metre, or B.Th.U. per cubic foot.

In considering the calorific effects of various fuels it is necessary for a true view of the conditions to take into account the air needed for combustion, for the fact must not be lost sight of that the combustion is a reaction between the fuel and the air (or the oxygen contained

in the air), and that both are necessary for the evolution of the heat generated.

If, then, in the case of gaseous fuels, we compare not the calorific values per cubic foot of gas (with unequal and undeclared quantities of air), but the calorific values per cubic foot of a gaseous mixture containing gas and air in the proportions needed for combustion, we find much smaller differences among the figures. Thus a cubic foot of

Hydrogen needs	for combustion	$2\frac{1}{2}$	cubic feet	of air
Carbon monoxide	,,	$2\frac{1}{2}$	,,	,,
Methane	,,	10	,,	,,
Ethylene	,,	15	,,	,,

So that the calorific value per cubic foot of combustible mixture will be for

Hydrogen,	$321 \div 3\frac{1}{2}$,	or 92	B.Th.U.	nearly
Carbon monoxide,	$320 \div 3\frac{1}{2}$,	or 92	,,	,,
Methane,	$998 \div 11$,	or 91	,,	,,
Ethylene,	$1580 \div 16$,	or 99	,,	,,

Coal gas containing, say, 25 per cent. of methane, 6 per cent. of ethylene and its homologues, 45 per cent. of hydrogen, 12 per cent. of carbon monoxide, and 12 per cent. of inert nitrogen and carbon dioxide, would have a calorific value of about 530 B.Th.U. per cubic foot, and would need about 4·8 cubic feet of air to burn a cubic foot of it; so that the calorific value per cubic foot of mixture would be nearly 91 B.Th.U.; but a producer gas, containing a much larger percentage of inert gases —say 2 per cent. of methane, 25 per cent. of hydrogen, 20 per cent. of carbon monoxide, and 53 per cent. of nitrogen and carbon dioxide—would have a calorific value of about 160 B.Th.U. per cubic foot, would need 1·3 cubic feet of air to burn a cubic foot of it, and would have a calorific value per cubic foot of mixture of only about 70 B.Th.U.

It is interesting to compare with these figures that for a coal-dust mixture. We found that a cubic inch of the coal we were considering needed 7 cubic feet of air for combustion. It weighed 0·05 lb., and would therefore on burning (if the calorific value of the coal were 8000 calories

per kilo., or 14,400 B.Th.U. per lb.) give out $0·05 \times 14,400$ or 720 B.Th.U. This is yielded by 7 cubic feet of the mixture (for the cubic inch of coal adds so little to the volume that we can neglect it) ; so that 1 cubic foot yields 103 B.Th.U., a figure of the same order as, but sensibly greater than, that for an equal volume of the mixture of any of the ordinary combustible gases with the right proportion of air.

In literature dealing with fuels we frequently come across the expressions "gross" and "net" calorific value. To understand these fully it is necessary to be clear as to the meaning of the terms "specific heat" and "latent heat."

SPECIFIC HEAT

The effect of adding heat to a substance is usually to raise its temperature. Heat will only flow naturally from a body at a higher to a body at a lower temperature, just as water will only flow naturally from a place at a higher to a place at a lower level. But whilst a calorie added to a kilogram of water will raise its temperature by one degree, a calorie added to a kilogram of mercury will raise its temperature by about thirty degrees, or to raise the temperature of a kilogram of mercury by one degree we need only about one-thirtieth of a calorie. This, like density, is an individual character of each substance, and it is expressed by saying that the "specific heat" of a substance is the amount of heat that is needed to raise the temperature of unit mass of it by one degree. Water has a higher specific heat than practically any other substance, and a higher specific heat in the liquid form than in the form either of ice or of steam. Here also, the specific heats of gases are usually expressed as calories per cubic metre, or B.Th.U. per cubic foot, for convenience. A few typical specific heats are given in the table opposite.

The specific heats of nearly all substances increase as the temperature gets higher ; the figures given opposite for solid or liquid substances hold only for ranges of temperature between, say, 0° and 200° C. For the discussion of problems connected with the use of fuel it is very desirable to know the specific heats of certain substances at high temperatures

such as reign in the combustion chambers of furnaces, but we have very little accurate knowledge of these, and have therefore to be content with approximations in dealing with these problems. The second columns of figures in the case of the gases are such approximations to the mean specific heats over a range from 0° to 2000° C.

	Calories per kilo. or B.Th.U. per lb.	Calories per cub. metre		B.Th.U. per cub. foot	
		0°C.-200°C.	0°C.-2000°C.	0°F.-400°F.	0°F-3600°F.
Iron .	0·19				
Copper .	0·09	..	..	..	..
Lead .	0·03	..	..	..	..
Carbon . .	0·31	..	..	..	..
Water .	1·00	..	..	..	..
Ice .	0·47	..	..	..	..
Steam .	0·466	0·386	0·619	0·043	0·070
Hydrogen .	3·408	0·310	0·358	0·035	0·040
Nitrogen .	0·243	0·305	0·358	0·035	0·040
Oxygen .	0·224	0·311	0·358	0·035	0·040
Air .	0·243	0·306	0·358	0·034	0·040
Carbon monoxide	0·251	0·306	0·358	0·034	0·040
Carbon dioxide	0·228	0·421	0·710	0·047	0·080

LATENT HEAT

When we apply heat to water we raise its temperature, but when the water begins to boil its temperature ceases to rise, and a thermometer immersed in the steam from it shows the same temperature (approximately 100° C.) as the water. Not until the whole of the water has been converted into steam can we get any further rise of temperature. The heat going into the water during the boiling has ceased to exist as heat, and has been absorbed in doing molecular work in converting the water into steam at the same temperature. We can measure the amount of heat

which has so disappeared, and we find it to amount to 537 calories for every kilogram, or 967 B.Th.U. for every pound, of water converted into steam. This figure is called the "Latent heat of evaporation" of water, or often the "Latent heat of steam." All substances behave similarly to water in this respect, though the "latent heats" of practically all other substances are much smaller than that of water. And all substances in changing from the solid to the liquid state absorb heat in a similar manner; thus a kilogram of ice at the freezing-point in becoming a kilogram of water at the same temperature absorbs 80 calories, which figure expresses the "Latent heat of fusion" of ice, often called the "Latent heat of water." In our present work we shall be concerned only with the latent heat of steam; and the only other point to remember is that this action is reversible: that if we remove heat from steam we shall not be able to reduce its temperature below 100° C. until the whole of it is converted into water, and that every kilogram of it in changing from steam at 100° C. to water at the same temperature will give out the 537 calories which were absorbed in converting it from water into steam.

NET CALORIFIC VALUE

It has already been said that all the substances which we use as fuel contain carbon or hydrogen or both, and that when they are burnt the oxygen of the air combines with the carbon to form carbon dioxide, and with the hydrogen to form water. When we determine experimentally the calorific value of a sample of coal, of oil, or of gas, we start with the whole of the materials at the ordinary temperature of the room—say 15° to 20° C.—and at the end the whole of the products are again brought to about the same temperature. Any water that is formed during the combustion, therefore, and which at the high temperature of the combustion would be formed as steam, has during the cooling been converted into water, and has given up to the calorimeter the whole of its latent heat, which has accordingly been counted into the calorific value of the fuel. It is pointed out that in actual operation the products of combustion are not cooled in the furnace to the ordinary temperature of a

room, but leave for the chimney-stack at a temperature at which the whole of the water formed is not liquid water, but steam. The steam, not having been condensed, has not given up its latent heat usefully in the furnace, but has carried it off with it, and the calorific value of the coal is therefore in actual practice lower than the value which was determined in the calorimeter. It is customary, therefore, to calculate from the analysis of the fuel the amount of water that will be produced from a kilogram on combustion, to calculate the amount of heat which this would contribute by being first condensed to water at 100° C. and then cooled as water to the temperature of the experiment, to subtract this amount from the calorific value (now spoken of as the "gross" calorific value) as determined, and to call the figure so arrived at the "net" calorific value of the fuel.

Suppose a coal containing 5 per cent. of hydrogen in its composition and 5 per cent. of moisture, and suppose that the calorific value has been determined at a temperature of 20° C. in the laboratory, to be 8000 calories. Each part of hydrogen combines with 8 parts of oxygen to form 9 parts of water; accordingly the 5 kilos. of hydrogen in 100 kilos. of coal will produce 45 kilos. of water, which with the 5 kilos. of moisture give us 50 kilos. in all, or 0·5 kilo. of water from 1 kilo. of coal. Each kilo. of water gives out 537 calories in changing from steam at 100° C. to water, and 80 calories in cooling as water from 100° C. to 20° C.: total 617 calories. From 0·5 kilo., then, we shall have had 308 calories, and the net calorific value of the coal will be $8000-308$, or 7692 calories.

A little consideration will show that this "net" calorific value is a purely arbitrary figure; it gives us, certainly, a nearer approach to the proportion of the total calorific effect of the coal used up in the furnace than the "gross" calorific value, but it leaves us entirely in the dark as to what that proportion actually is. In the first place, the gases leaving by the stack are always very considerably higher in temperature than 100° C., and, in the second, they do not consist entirely of steam. There is present the whole of the carbon dioxide produced from the carbon of the fuel, the whole of the nitrogen associated as air with the oxygen which the fuel has consumed, and the whole of any excess air beyond that

actually used in the combustion; and all of these gases are at the high temperature of the flue, and are carrying away heat which in the calorimetric determination was recovered from them.

Suppose the coal just mentioned to contain 80 per cent. of carbon. Then, since 12 parts of carbon need 32 parts of oxygen for combustion, a kilogram of the coal will need for

0·8 kilo. of carbon,	2·13 kilos. of oxygen
0·05 kilo. of hydrogen,	0·4 ,, ,,
—in all,	2·53 ,, ,,

but in the air 23 kilos. of oxygen are associated with 77 kilos. of nitrogen, so that 2·53 kilos. of oxygen will bring in 8·47 kilos. of nitrogen (thus 1 kilo. of the coal needs 11 kilos. of air for its combustion). The products of combustion will be 2·93 kilos. of carbon dioxide, 0·45 kilo. of water from the combustion, and 0·05 from the moisture in the coal—total, 0·5 kilo. and 8·47 kilos. of nitrogen. Suppose these products to leave the furnace at a temperature of 250° C. (482° F.). How much heat do these gases carry away, above what they would do at 20° C.?

To heat 2·93 kilos. of carbon dioxide 230° C. needs $2{\cdot}93 \times 230 \times 0{\cdot}228 =$	153·7 calories.
To heat 0·5 kilo. of water to 100° needs $0{\cdot}5 \times 80 \times 1 =$	40·0 ,,
To evaporate the water to steam at 100° needs $0{\cdot}5 \times 537 =$	268·5 ,,
To heat the steam from 100° to 230° needs $0{\cdot}5 \times 130 \times 0{\cdot}466 =$	30·3 ,,
To heat 8·47 kilos. of nitrogen 230° needs $8{\cdot}47 \times 230 \times 0{\cdot}243 =$	473·3 ,,
Hence to raise the whole of the products of combustion from 20° to 250° C. needs	965·8 ,,

The actual calorific effect of the coal in the furnace is therefore 8000 − 966, or 7034 calories: a figure with much more meaning in it than the "net" value of 7692.

Clearly, had there been excess air present in the example just

considered, that air entering the furnace at atmospheric temperature and leaving at 250° C. would have further reduced the actual calorific effect of the coal ; and in any individual case the actual amount of this reduction can only be found by having analyses both of the coal and of the flue gases, and a determination of the temperature in the flue. This, of course, is actually done in boiler tests : the present discussion of the subject is only to show that the so-called "net" calorific value is a figure of no real significance, and to indicate how figures that have real significance are to be obtained.

TEMPERATURE OF IGNITION

In order that the chemical action between a so-called combustible and the oxygen of the air, which we call combustion, may set in, the materials must not be below a certain temperature, which is called the temperature of ignition, or "kindling-point." Coal, coke, wood, oil or other combustible may lie about in contact with the air, or a stream of coal-gas may issue into the air, at ordinary temperatures, and no combustion will take place, during however long a period of time. We start combustion by raising some small portion of the combustible and the adjacent air to the necessary temperature, by bringing them into contact with some other object at a high temperature, such as a lighted match, a torch, a red-hot piece of metal, or an electric spark.

The portions so treated burn. But whether the combustion is to be continuous, whether the next-coming portions are to burn or whether, the match having been removed, the action is to end with the combustion of the small portions which it set alight, depends upon whether or not these next-coming portions can be raised to the kindling-point. The first portions which burn give out heat, of course. Some of this heat is lost by radiation and conduction into surrounding objects ; some of it is spent in heating up the neighbouring portions of combustible. If the heat so spent be enough to raise these neighbouring portions to the kindling-point, they in their turn will burn, will set alight their neighbours, and so the combustion will go on successively and continuously. If the heat evolved be not sufficient to effect this successive ignition, the combustion will not

continue, but "go out." Most ordinary combustibles evolve far more heat than is sufficient for this purpose ; but if a great deal of heat is needed to raise the temperature of the fuel, in consequence of its being very damp, for example, or if the kindling-point be very high, and the surroundings such as to absorb a large proportion of the heat produced, it may be difficult at first to secure continuous combustion. Everyone is familiar with the difficulty of lighting an ordinary domestic fire when the materials are a little damp and the iron bars of the grate are cold, and knows how much easier it is to relight it if the materials are all dry, and especially if the iron and fire-clay structure of the grate has not had time to get cold since the fire was last burning.

A combustion already proceeding may be stopped if any circumstance arises which forcibly absorbs so much of the heat of combustion that not enough is left to raise the on-coming portions of combustible to their kindling-point. The classical experiment of putting out a candle by bringing over the flame a spiral of heavy copper wire, the "blowing out" of a flame by a current of cold air, or the extinction of a gas flame as the gas passes through a sheet of wire gauze are all examples of this; and on the large scale a precisely similar thing may happen if, for example, a flame impinges directly on the comparatively cold tubes of a boiler.

Different substances have very different kindling-points. There are substances, like zinc-ethyl, which take fire if brought into contact with air at the ordinary temperature ; carbon disulphide will burn if a hot glass rod, far below red-heat, be dipped into it ; hydrogen gas takes fire at a red-heat, while methane will not burn till a higher temperature is reached.

The approximate kindling-points of some of the commoner combustible gases are given in the following table (Dixon and Coward, *Trans. Chem. Soc.*, 1909, 95, p. 514) :—

	In Oxygen °C.	In Air °C.
Hydrogen . . .	580–590	580–590
Methane . . .	556–700	650–750
Carbon monoxide . .	637–658	644–658
Acetylene . . .	400–440	406–440

In general, the volatile constituents of coal which are expelled on carbonisation have lower kindling-points than the carbonaceous residue which is left behind, so that it will not be so easy to start the combustion of powdered coke or anthracite as of bituminous coal.

ATTAINABLE TEMPERATURE

In devising means for the best and most economical utilisation of heat, the object to be attained has always to be taken into consideration, and one of the first elements of difference amongst different applications of heat lies in the temperature which it is necessary to attain. Heat will only flow from a higher temperature to a lower, and however much heat we may have at a low temperature, it will never enable us to effect even a small operation at a higher temperature. It needs a great deal more heat to produce a hot bath than a saucepan of boiling water ; but all the heat in the hot bath will not cook an egg for us, nor will all the heat stored in the largest locomotive boiler avail to melt the smallest piece of silver. We may need to raise steam in a boiler, or to produce steel in an open hearth furnace : for either purpose we may use coal, directly or indirectly ; but the arrangement which turned out to be the best and most economical for the one purpose might be quite impracticable, or greatly inferior to some other arrangement, for the other, in which the attainment of a very high temperature is vital.

These considerations lead to the question: What is the highest temperature attainable by the use of any particular fuel and how can it be ascertained? An example or two will show how far this question can be answered.

Consider first the coal mentioned in the discussion on " net " calorific value. The heat given out by 1 kilo. is 8000 calories, and clearly the highest possible temperature that can be reached by its combustion will be reached if it is spent entirely in heating the products of combustion. We have seen that in heating those to 250° C., 966 calories are used, and 7034 calories remain. Now for each degree of further rise in temperature we shall have to spend on—

2·93 kilos. of carbon dioxide,	$2{\cdot}93 \times 0{\cdot}421 =$	1·234	calories
0·5 kilo. of steam,	$0{\cdot}5 \times 0{\cdot}619 =$	0·310	,,
8·47 kilos. of nitrogen,	$8{\cdot}47 \times 0{\cdot}358 =$	3·033	,,
	Total,	4·577	,,

say 4·6 calories. The attainable temperature will then be $\frac{7034}{4{\cdot}6}$ or 1530° above 250°, or to 1780° C.

If we had supposed this coal to have been burnt, not with the exact quantity of air necessary to burn it, but with a 50 per cent. excess of air, then we should have had an additional 5·5 lbs. of air to heat up. To raise this to 250° C. (it is necessary to make the calculation in two stages with any fuel containing hydrogen, because of the latent heat of steam coming into the question, and also because of the specific heat of steam being different from that of water, but any temperature at or above 100° C. might be chosen as the first stage ; we are only using 250 °C. here because we had some of the figures for that temperature from a former calculation) would need $5{\cdot}5 \times 230 \times 0{\cdot}243$, or 307·4 calories, and would reduce the available heat remaining at that temperature from 7034 to 6727 calories. And it would add to the heat needed to raise the gases through each degree of further rise $5{\cdot}5 \times 0{\cdot}358$ or 1·969 calories, making that $4{\cdot}577 + 1{\cdot}969$, or 6·546 calories. So that the temperature would rise $\frac{6727}{6{\cdot}546}$ or 1028° above 250°, or to 1278° C.

A similar calculation would be easily made for any other combustible, or for any other amount of excess of air.

These calculations show how considerably the attainable temperature is reduced by the presence of excess air, and as the transmission of heat from the hot gases to the objects which are to be heated, whether meal ingots or boiler tubes, is the more rapid as the difference in temperature between them is the greater, we can see that it is important for efficiency and rapidity of working to have as high a temperature as possible in the combustion chamber. For this reason, as well as because the excess air carries off heat with it uselessly into the flues, excess air is to be avoided as far as is practicable.

If we go too far in this direction, and reduce the air below what is

needed for complete combustion, we get smoke. Smoke involves loss, for it means that some of the fuel is going through the furnace unburnt, and it also constitutes a nuisance. The actual loss of unburnt carbon in black smoke is not very great, for a very small amount of actual carbon or soot will make a large volume of dense-looking smoke; but besides the actual carbon there is always under these circumstances a quantity of unburnt combustible gas which makes little or no show to the eye, and the total amount of such unburnt combustible substance may be quite considerable.

COMPOSITION OF FLUE GASES

When combustibles containing carbon are burnt the carbon combines with the oxygen of the air and forms carbon dioxide. This carbon dioxide goes off in the flue gases along with the nitrogen of the air which was used in combustion, and with any excess or surplus air which has passed through the furnace. The greater the amount of such surplus air the smaller will be the proportion borne by the carbon dioxide to the total flue gases; and the percentage of carbon dioxide in the flue gases is frequently used (with or without a determination of the free oxygen also present) as an index of the completeness and efficiency of the combustion. To attain complete combustion with as small an excess of air as possible is to achieve the highest efficiency.

It is to be noted here, however, that the figure denoting the percentage of carbon dioxide in the flue gases when that highest efficiency has been achieved will depend upon the composition of the combustible. Let us take some examples to make this clear:

1. Suppose the combustible to be pure carbon. If 12 grams of carbon be burnt it will need 32 grams of oxygen, the volume of which at N.T.P. (0° C., and 760 mm. barometer) would be 22·4 litres. It will form 44 grams of carbon dioxide, which will have the same volume, 22·4 litres, as the oxygen used in its production. The air from which the oxygen was obtained contained (very nearly) 21 per cent. of oxygen and 79 per cent. of nitrogen by volume; the flue gases will contain all the nitrogen of the air that was used and a volume of carbon dioxide exactly equal to that of the

oxygen that has been taken out. No further calculation is needed to see that they will consist of 21 per cent. of carbon dioxide and 79 per cent. of nitrogen. We cannot, using carbon as combustible, reach a higher percentage of carbon dioxide in the flue gases than 21. A lower percentage, such as 16, would mean excess air; for if there be 16 of carbon dioxide in 100, 21 will be contained, not in 100, but in 131, and with every 100 of "true" flue gas consisting of nitrogen and carbon dioxide there are 31 of excess air.

2. Suppose the combustible to be carbon monoxide gas and that we burn 28 grams of it. That will occupy 22·4 litres, will need 16 grams, or 11·2 litres, of oxygen, and will form 44 grams, or 22·4 litres, of carbon dioxide. The flue gases will consist of the nitrogen formerly associated with the oxygen, 42·1 litres, and 22·4 litres of carbon dioxide. The percentage of carbon dioxide will be, therefore, $\frac{2240}{64.5}$, or 34·7. If in this case we had a percentage of 21 (which would represent the highest possible efficiency had the combustible been carbon), it would mean that 34·7 of carbon dioxide were present in $\frac{3470}{21}$, or 165 of flue gas, and that with every 100 parts of original air actually used, 65 parts of excess air had gone into the furnace.

3. Suppose (extreme case) the combustible to be hydrogen. Then 2 grams, occupying 22·4 litres, would take 16 grams, or 11·2 litres, of oxygen, and form 18 grams, or 22·4 litres, of gaseous steam. When cooled (and the analysis is of course always made on the cold gas) this steam would condense as water, and the flue gas would consist of 42·1 litres of nitrogen, with no carbon dioxide at all.

4. Take now two ordinary combustibles containing both carbon and hydrogen. First, the coal we have used before, with 80 per cent. of carbon and 5 per cent. of hydrogen:

80 gr. carbon take 213·3 gr. oxygen, 149·3 litres, form 293·3 gr. CO_2, 149·3 litres.

5 gr. hydrogen take 40 gr. oxygen, 28·0 litres, form 45 gr. steam, 56·0 litres.

Nitrogen associated with 177·3 litres oxygen is $\frac{79}{21} \times 177{\cdot}3$, 666·5 litres.

Flue gases are 666·5 litres nitrogen, 149·3 litres carbon dioxide, 815·8 litres.

Percentage of carbon dioxide, $\frac{14930}{815 \cdot 8} = 18 \cdot 3$.

Second, a fuel oil, containing, say, 88 per cent. of carbon and 11 per cent. of hydrogen :

88 gr. carbon take 234·6 gr. oxygen, 164·2 litres, form 322·6 gr. CO_2, 164·2 litres.

11 gr. hydrogen take 88 gr. oxygen, 61·6 litres, form 99 gr. steam, 123·2 litres.

Nitrogen associated with 225·8 litres oxygen is $\frac{79}{21} \times 225 \cdot 8$, 849·4 litres.

Flue gases are 849·4 litres nitrogen, 164·2 litres carbon dioxide, 1013·6 litres.

Percentage of carbon dioxide, $\frac{16420}{1013 \cdot 6} = 16 \cdot 2$.

Whilst, then, a percentage of 16·2 would mean, using the oil fuel, absolute theoretical efficiency, the same percentage, using the coal, would mean excess air to the extent of $\frac{1830}{16 \cdot 2} - 100$, or 13 volumes with every 100 volumes of useful air introduced. Clearly, then, we should be very unjust to the oil fuel if we judged it on the figures of our records for coal.

Different coals vary to some extent in the relative proportions of carbon and hydrogen which they contain, but these variations are so small that from this point of view we may look on them as being all alike ; but if we are comparing them with coke on the one hand, or fuel oil on the other, the mere percentage of carbon dioxide in the flue gases must not be taken as a sufficient index to efficiency of combustion, and we must know the amount of carbon monoxide—if any, in which case combustion has not been complete—and of free oxygen, a direct index to the amount of excess air.

When we have these figures, and also the temperature of the flue gases, we are in a position to calculate, in the same way as was illustrated on p. 32, the amount of heat, or the percentage of the total calorific value

of the fuel, which is lost in the flue gases. Frion gives a table of approximate percentages, from which the following is taken; the lower temperatures and the corresponding percentages of carbon dioxide are such as might occur in boiler furnaces, the higher ones such as might occur in metallurgical furnaces:—

Flue Gases			Chimney Losses
Temperature		Per cent. CO_2	Per cent. of calorific value of coal
180° C.	360° F.	10–12	14–11
		14	9
300° C.	570° F.	10–12	25–18
		14	15
600° C.	1110° F.	12–15	40–35
		17	31
1000° C.	1830° F.	12–15	68–61
		17	56

VOLUME OF FLUE GASES

While considering the question of flue gases it may be well to point out how not only their composition, or the relative volumes of their constituents, but also their absolute volume, is to be ascertained.

The volume of a given mass of any gas is not a fixed quantity, but depends upon and varies with two conditions—namely, its pressure and its temperature. If the pressure be varied the volume of the gas varies in the inverse proportion (Boyle's law). If the temperature be varied the volume increases or diminishes with each degree of rise or fall of temperature by $\frac{1}{273}$ or 0·00366 of the volume which it occupies at 0° C. It is clear from this that if the gas were cooled to 273° below 0° C., and if the diminution in volume went on in the same way to the end, and no change such as the liquefaction or solidification of the gas were to occur, the volume of the gas would be reduced to zero. This temperature of –273° C. is hence called the "absolute zero," and temperatures are often reckoned from this zero and called absolute temperatures. Obviously the value of the absolute temperature is obtained by adding 273° to the

centigrade temperature: thus 150° C.=288° A. If we use absolute temperatures the relation between the volume of a given mass of gas and its temperature can be very simply expressed by saying that the volume is proportional to the absolute temperature. If we are using Fahrenheit degrees the absolute zero is 1·8 times 273, 491·4, or say 492° below the freezing-point, or 460° below the zero of the Fahrenheit scale; so that we must add 460 instead of 273 to the Fahrenheit temperature to get the absolute temperature in Fahrenheit degrees: thus 60° F.=520° A. in this scale.

One more convention before proceeding to calculate out an instance. When, above, we took 2 grams of hydrogen, or 32 grams of oxygen, or 28 grams of carbon monoxide (what the chemist calls the "molecular weight" in grams in each case), as occupying 22·4 litres, the measurement was supposed to be made, in each case, at the normal or standard pressure and temperature of 760 mm. of mercury column and 0° C. When we correspondingly speak of 18 grams of steam as occupying 22·4 litres, this measurement is supposed to be made under the same conditions. Now under these conditions steam would not exist, but would condense to water; but though this is the fact, yet, if we wish to make any calculations in regard to the volume of steam under such conditions that it would exist as steam, we arrive at correct results from making the assumption that if it could have existed as steam at 760 mm. pressure and 0° C., then 18 grams of it would, under those conditions, have occupied 22·4 litres.

Now take the coal in example No. 4 above, and suppose that the temperature of the flue gases as they leave the boiler is 260° C. or 533° A. They will be composed now of carbon dioxide, steam and nitrogen, and the volumes produced by burning 100 grams of coal will be:

Carbon dioxide	$\frac{533}{273} \times 149{\cdot}3 =$	291·5	litres
Steam	$\frac{533}{273} \times 56{\cdot}0 =$	109·3	,,
Nitrogen	$\frac{533}{273} \times 666{\cdot}5 =$	1301·3	,,
Or a total volume of		1702·1	,,

If the barometric pressure be 740 mm. instead of 760, then this total volume will become $\frac{76}{74} \times 1702{\cdot}1$, or 1748·1 litres, and each of the constituent volumes will be correspondingly increased.

If we convert these metric figures into pounds and cubic feet, taking a kilogram as 2·2 lbs. and a cubic foot as 28·3 litres, we find that the flue gases from a pound of coal will occupy at 260° C.

$$\frac{17021}{2{\cdot}2 \times 28{\cdot}3} = 273{\cdot}4 \text{ cubic feet}$$

If, further, we consider that these gases in the furnace itself may reach temperatures about 1300° C. or more, and if, for convenience, we take 1326° C. or 1599° A., because 1599 is three times 533, we find that there the products of combustion from every pound of coal will occupy a space of three times 273·4, or 820 cubic feet. These figures give some idea of the dimensions that have to be taken into account in designing furnaces and flues. If we take, for example, the boilers at Vitry (p. 133), each of which may burn close on 20,000 lbs. of coal per hour, we see that 20,000 × 820, or 16,400,000 cubic feet of gases will pass through the combustion chamber per hour, or about 4600 cubic feet per second; and if the speed of the gases is not to exceed 20 feet per second there must therefore be an area of path of not less than 230 square feet for them.

HISTORICAL AND GENERAL

The earliest attempts to use coal-dust or powdered coal as fuel date back nearly a hundred years. Henschel, of Cassel, in 1831 employed a current of air charged with coal-dust in heating brick kilns, in soldering, and in other furnace applications, and Putsch, in England, endeavoured to apply it in glass manufacture.

Whelpley and Storer in 1866 took out a patent for introducing powdered coal as an auxiliary into a grate fired furnace. The powdered coal was fed through a number of openings into the fire-box of the furnace, was ignited by the fire in the grate and burned in the supply of air that was already being introduced into the furnace.

Crampton between 1866 and 1873 succeeded in burning coal-dust in metallurgical furnaces and also under boilers, by means of a fan, and he devised an ingenious apparatus for introducing the powdered fuel into the furnace. The coal he used appears to have been very coarse, however, in comparison with modern powdered fuel.

West and McAuley in America in 1876 and 1880 took out patents for a powdered coal feeder very similar to many of the modern forms. In this a screw conveyor took the coal from a bin and dropped it down a vertical pipe into a horizontal pipe leading to the burner. In this pipe it was carried along to the burner by means of a blast of air, mixed with which it entered the furnace.

Several forms of apparatus were devised in Germany between 1890 and 1895 for burning powdered coal. Nearly all of these consisted of a bin for the coal, the issue of which was regulated by slides or by revolving wheels at the bottom of the bin, aided by some regular tapping apparatus. The coal fell directly into a tube through which a current of air passed, which carried it into the furnace much in the manner of a modern burner. In one of these forms of apparatus, which appears to have been for some time in actual use and to have worked with a high degree of efficiency, the fuel was carried into the furnace by the suction of a chimney draught, not by the direct pressure of a blower or fan. As the temperature at the chimney foot is given, in the accounts of some trials, as varying from 478° to 531° C. (892° to 988° F.), it is clear that a large amount of heat must have gone to waste in the chimney gases. These German patents were nearly all concerned with burners, and little information is to be found on the subject of the production of the powdered fuel or of the degree of its fineness. Lancashire and fire-tube boilers gave in many instances satisfaction with these arrangements; water-tube boilers as a rule did not.

About 1900 the introduction and improvement of mechanical stokers made smokeless combustion possible and took away one powerful incentive towards the development of powdered fuel firing.

In the *Journal of the Society of Chemical Industry*, 1905, xxiv. 369, there is an interesting paper by Eustace Carey in which he discusses generally

the problem of powdered fuel, mentions Whelpley and Storer's work, and an improvement on it by Stevenson, of Valparaiso, and describes an installation at Haydock, of the Schwartzkopff Coal-Dust Firing Syndicate, in which the coal is dried and pulverised much as in present-day installations. He shows that, using 500 tons of coal per week and working only one shift per day, the cost for drying, grinding and burning, with power, is about 11·1 pence per ton, but that if two shifts per day had been worked it would have been only 7·7 pence. In the discussion, possibilities of using powdered coal instead of gas firing, and thus saving producer losses, of using it where coal was high in price, and therefore grinding costs were of less weight, and of using by its means low-grade fuels which were uneconomical or impracticable to use in the ordinary way, were all brought out.

In 1906 Mr S. Sorensen, in the *Engineering and Mining Journal*, described experiments with powdered coal in a reverberatory smelting furnace, which seemed to show that it could be economically used, though the then existing mechanical difficulties had prevented him for the time from introducing it permanently; and Mr C. Shelby, two years later, in the same journal, gave an account of further work of a similar kind. From that time onward the subject attracted more general attention, especially in the United States and Canada; the difficulties in the application of powdered coal to furnace work were gradually overcome, and it came continually into wider use. In 1919 there is said to have been used in the United States about 11,000,000 tons of powdered fuel, of which about 6,000,000 tons were used in the cement industry, 2,000,000 in the iron and steel industry, 1,500,000 in the copper industry, and about 200,000 for the generation of power. Since then a much wider development has taken place, especially in the amount used under boilers; and other countries, especially France, have also adopted it on a very considerable scale. The installations in this country are mostly small, but they are increasing in number, and as the economies which the use of powdered coal permits, and the other advantages which it carries in its train, become more widely known, this increase, both in number and in the size of individual installations, will become continually more rapid.

GENERAL DESCRIPTION OF INSTALLATION

A typical installation for the burning of powdered coal includes arrangements for (*a*) breaking, (*b*) drying, (*c*) pulverising the coal, (*d*) transporting it to the furnace, and (*e*) feeding it to the burner. It also includes the necessary arrangements for supplying the air needed for combustion.

The systems in use divide themselves sharply into two: the unit system, in which the coal is pulverised at the furnace, and the multiple system, in which the powdered coal is prepared at a central station and is transported in the powdered form to any number of furnaces that may be included in the installation.

In the unit system there is, of course, a separate pulveriser for each furnace; there is therefore no need for any transport system, save for the coal as delivered to the pulveriser, and because of the short distances through which the powdered coal has to travel, and because there is no storage of pulverised coal in bins, there is seldom any need to install drying apparatus for the coal.

A diagrammatic picture of the usual arrangements for a multiple system installation is shown in Fig. 1.

The coal is delivered from trucks on rails into the car hopper, from which a reciprocating feed delivers it to the crusher, where it is broken down to pieces of about $\frac{5}{8}$ inch to $1\frac{1}{4}$ inch cube. It is seized by the buckets of the elevator and dropped into the crushed coal storage bin, whence another reciprocating feed drops it upon a magnetic separator, to remove any accidental "tramp" iron. From the separator it enters the cylinder of the drier, in which its moisture is removed by a current of hot flue gas, and from the other end of which the dried coal falls into the well of another bucket elevator, which delivers it into the dry coal bin. From the dry coal bin it is fed to the pulverising mill, and the finely pulverised coal is carried, by the current of air produced by the exhaust fan, through the fan and into the cyclone collector. Here the air and the powdered coal separate, the air returning to the pulveriser and the coal gathering in the lower part of the collector. A screw conveyor, or other means of

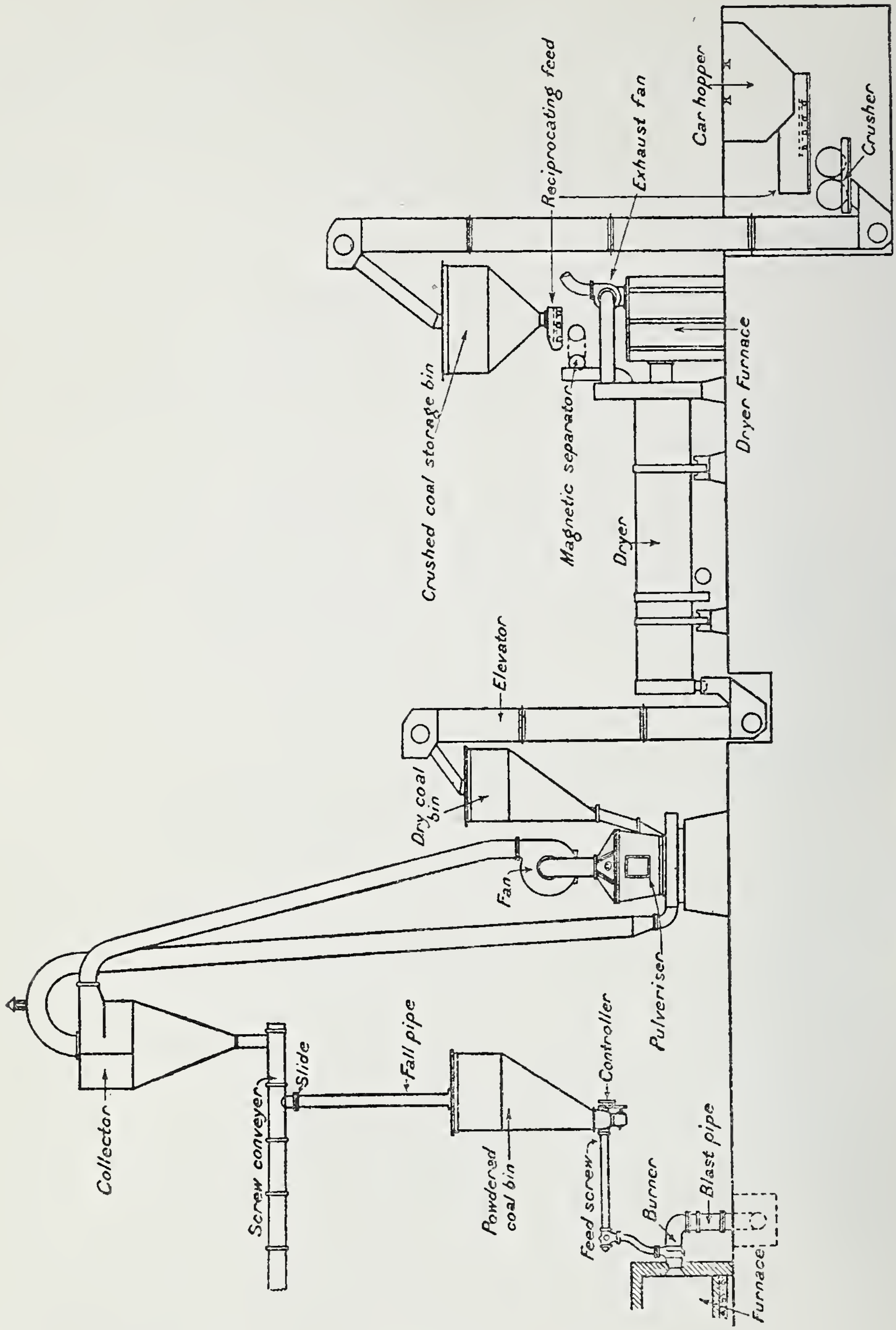

FIG. 1.—GENERAL ARRANGEMENT OF POWDERED COAL FIRING INSTALLATION

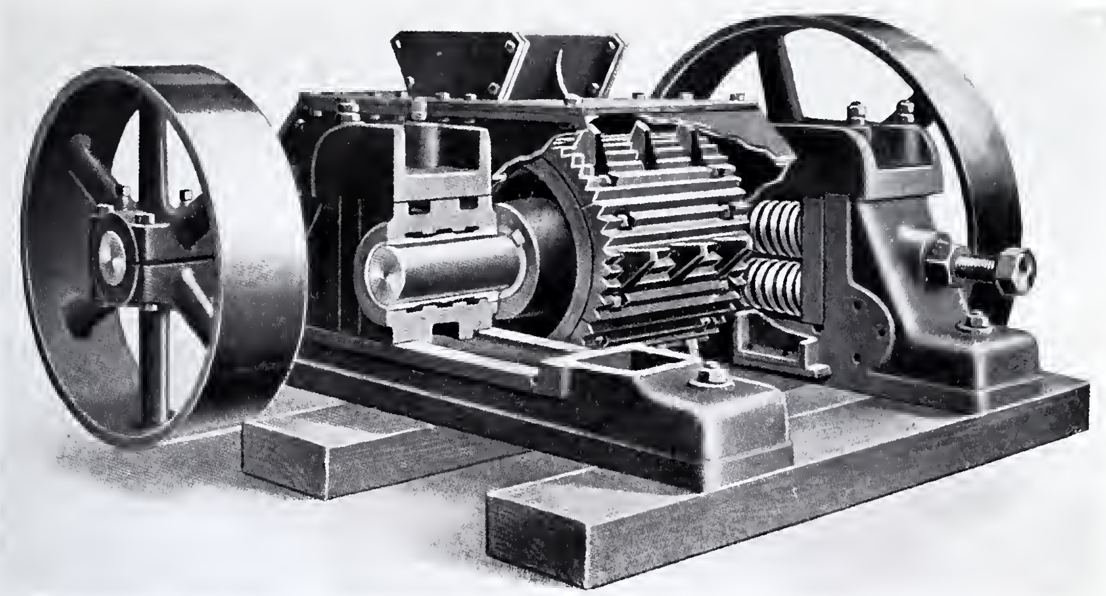

Fig. 2.—Fuller Breaker

transport, carries the powdered coal from the collector through a system of main piping, past the various furnaces, and at each furnace is a fall pipe, opened when necessary, through which the coal drops into the furnace coal bin. From the bottom of this the coal is fed, through some form of regulator to control the rate of flow, into a feed-screw which delivers it to the burner. Here it is mixed with the appropriate amount of air, enters the furnace, and is burnt.

As will be shortly seen, different systems effect these various operations by methods showing great variety in every detail. Choice among these various systems can only be judiciously made after considering all the conditions and circumstances of the work which a proposed installation will have to do. No one system embodies in all its parts every advantage, and a quality which it is important to secure in one installation may be of secondary consideration in another. The separate members of a "system," too, often hang rather loosely together, and it may in any instance be found that an eclectic combination, formed of parts derived from different "systems," may be the best suited for the circumstances under which it has to work.

In the following pages the forms of plant usually employed for the various operations in the preparation, transport and burning of powdered coal are described in sufficient detail for an understanding of their modes of working, and of the requirements which they are intended to satisfy.

CRUSHING

If the coal is larger than the size with which the pulverising mill is to be fed—usually from $\frac{5}{8}$ inch to $1\frac{1}{4}$ inch cube, according to the size of the mill—it must be broken down to that size by any of the usual devices, such as a Jeffrey breaker or crushing rolls. With a substance like coal, it is highly desirable that the crusher should be completely cased in, and that the outer side of the casing should be as free as possible from angles, ribs, pockets, or projections of any kind, in the corners of which dust can accumulate.

In many installations the coal as received is already in a mechanical

condition suitable for direct delivery to the pulverising mills, with or without preliminary drying. Indeed one of the economical advantages of powdered fuel firing is that it permits of the use of small coal and slack, which are obtainable in large quantities and at cheap rates because they are either unusable on grates, or at least so much less suitable for grate firing than better qualities of coal that it is more economical to use these better qualities, in spite of their higher price, than to use the cheaper stuff.

Crushing rolls made by the Fuller Company are shown in Fig. 2 and may be taken as illustrating the requirements made of a crusher. The pressure between the rolls can be varied by adjusting the springs which press against the movable bearing. The roll shells may be smooth or corrugated, and may be supplied also with the "slugger teeth" shown, the object of which is to nip and fracture the large lumps of coal and draw them into the crushing zone. These are made in sizes dealing with 8 to 25 tons per hour, and needing from 5 to 15 h.p. to drive them.

The crushed coal is delivered to the drier, where the coal is to be dried, or directly to the pulverising mill, if it is dry enough to be used in its natural state (this will usually be so in unit systems) ; but although some of the mills have arrangements for dealing with casual pieces of iron entering with the coal, it is a usual and a wise precaution to pass the coal on its road from the crusher over some form of magnetic separator, so as to remove any such accidental iron content, which otherwise might either injure the pulverising mill or interrupt its work. Fig. 3, also due to the Fuller Company, shows a magnetic separator of the pulley type at work, delivering the coal from the crusher to a chute, and carrying on any "tramp" iron to the sloping board on the right. The inset in the same figure shows a magnetic separator of the fixed type, which would be placed either close over the coal at the end of the belt, or at the bottom of the chute.

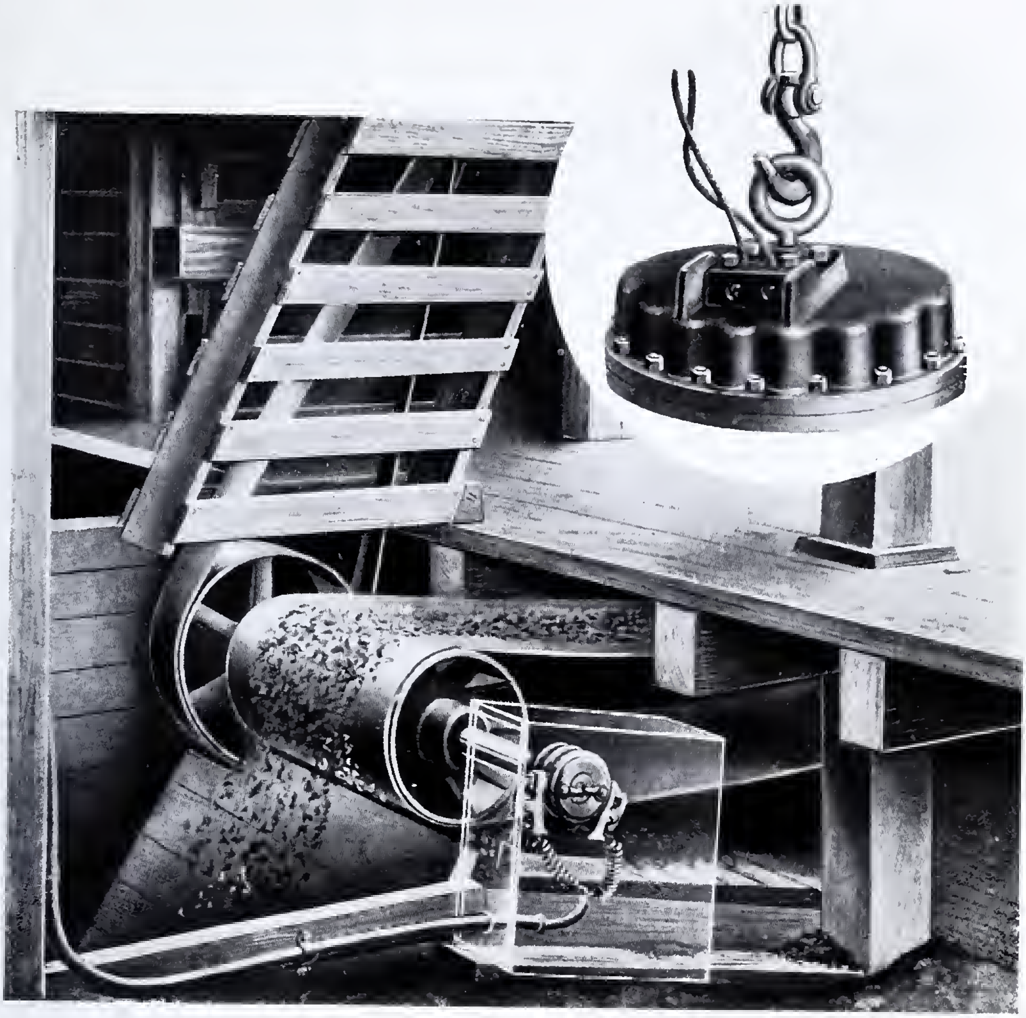

Fig. 3.—Belt and Magnetic Separator

DRYING

In most multiple plants with a central coal preparation system the coal is dried after crushing, so that its water-content is reduced to 1·0 per cent. or below.

Dry coal grinds more easily than damp coal; it is less ready to agglomerate and form bridges in storage bins or obstructions in pipes, and less likely therefore to lead to irregular feeding and interruptions to the continuity of working of the plant. Further, if the moisture be not removed from the coal before use it has to be evaporated in the furnace, lowering to some extent the attainable temperature, and carrying off into the chimney all the heat needed for its evaporation; and of course to produce a given weight of combustible a greater weight of wet than of dry coal must be put through the mills and transported—99 tons, for instance, containing 10 per cent. of water, against 90 tons if dried down to 1 per cent.

Whilst it may be worth while to pay something to secure the even and economical working of the plant, and in the case of certain furnace work to attain the highest possible temperature in the furnace, it must yet be remembered that the removal of moisture by special drying plant is not in itself an economical or efficient process. In the tests of the Oneida Street Power Plant of the Milwaukee Electric Railway & Light Company, referred to on p. 117, the following data regarding the drier are given :—

Moisture in coal entering drier, 5·6 per cent.
   ,,   leaving drier, 1·6 per cent.
Reduction of moisture, 4 per cent. or 80 lbs. per ton.
Energy absorbed by drier, per ton of coal dried, 1·53 kw. hour.
Equivalent in coal (at $1\frac{1}{2}$ lbs. per kw. hour), 2·28 lbs.
Coal used in drier per ton of coal dried, 25·66 lbs.
Total, coal and energy, expressed as coal, 27·94 lbs.
Calorific value of coal per lb., 11,880 B.Th.U.
Temperature of coal entering drier, 88·2° F.
   ,,   leaving drier, 237·9° F.

If we assume the moisture of the coal to be converted into steam at 212° F. and to leave the drier at that temperature, the heat absorbed by the moisture from a ton of coal will be

$$80\ (\overline{212-88}+967)=87{,}280\ \text{B.Th.U.}$$

But the actual calorific value of the coal used to effect the operation is

$$27{\cdot}94\times 11{,}880=331{,}930\ \text{B.Th.U.}$$

Thus little more than a quarter of the energy put into the drier has been spent in the operation of drying; the rest has gone in heating the coal to 238° F., in heating the excess air that has passed through the furnace, and in radiation and other furnace losses. As far as pure economy of evaporation goes, the removal of the water would probably be effected much more economically in the furnace, and driers might well be dispensed with where the other considerations above enumerated do not apply. Whether or not they apply, and what weight must be given to them, must be settled for each individual installation according to its circumstances.

In this connexion it may be well to point out the difference between moisture and what may be called "constitutional water" in a coal. The figure given as "water," or sometimes "moisture," in the statement of the analysis of a coal is the percentage of water which the sample loses on being kept at or just over the boiling-point of water till it ceases to lose any more. Two coals might be chosen, however, both showing 10 per cent. of water in the analysis, such that, if they were kept in a dry room till they ceased to lose moisture, one would lose, say, 8 per cent., whilst the other would lose only 2 per cent. Both of these coals might then look, and feel, perfectly dry. If they were then dried further at the boiling-point of water they would lose the remaining 2 per cent. and 8 per cent. respectively. The 8 per cent. and 2 per cent. which they respectively lost in dry air at the ordinary temperature represent extraneous water or moisture; the other portion in each case is constitutional water. It is the moisture only which causes the "wetness" of the coal and tends to produce agglomeration or clogging when the coal is finely ground; and there are many coals (the Northumberland steam coals are an example) which, though containing 6 or 8 per cent. of "water," are yet dry and dusty, and need no drying as a preparation for pulverisation and for

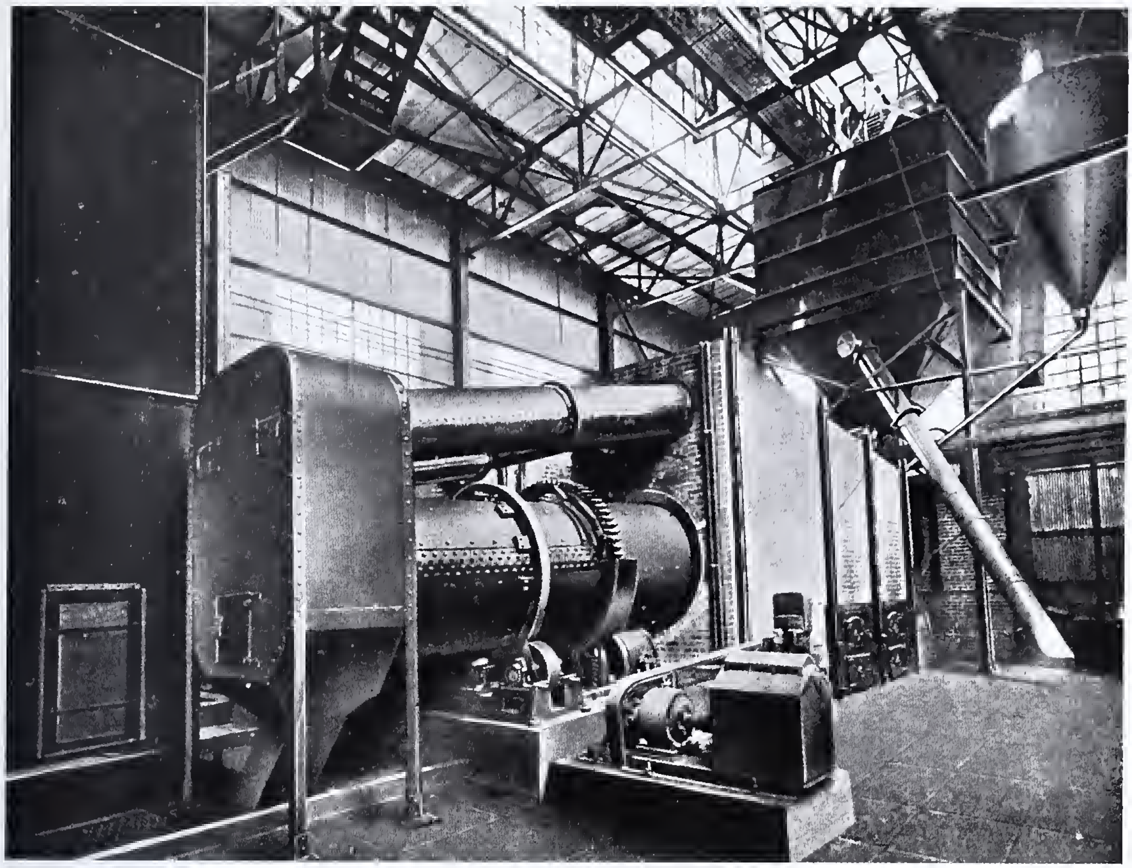

Fig. 4.—Fuller Rotary Drier

storage or transport of the powder produced. Most lignites, dried down to a water-content of 7 or 8 per cent., show no sign of external wetness; and the same is true of peat, with a much higher content still.

In 1921 a number of tests were carried out at the Oneida Street Station by Mr H. Kreisinger, on behalf of the Bureau of Mines (H. D. Savage, use of Powdered Fuel under Steam Boilers, American Iron & Steel Institute, May 1921). Most of these were worked on coal dried to contain from 1·5 to 3·5 per cent. of water, but three were worked on the undried coal, containing 7·7 to 8·2 per cent. The report on these was: "The results of the tests show that the completeness of the combustion was as good as with the dried coal. There was no loss due to CO in the flue gases, and the losses due to combustible in the refuse averaged only 0·3 per cent. for the three tests, which is in fact less than the average with the dried coal. The losses due to moisture in coal (*i.e.* heat carried away by the steam from this moisture) of course increased by 0·5 to 0·6 per cent., which increase is at the rate of about 0·1 per cent. for every 1 per cent. of increase of moisture in the coal. The average decrease in the boiler efficiency for the three tests is about 0·7 per cent., which checks closely the increase in the losses due to increased moisture in the coal. It seems, therefore, that it is not necessary to dry the coal down to 1 per cent. of moisture in order to get good boiler efficiency. In fact it seems that most of the Eastern coals can be pulverised and burned with good results without drying."

To dry the coal a temperature of at least 212° F. is necessary so that the moisture may be removed as steam, and for rapidity of action a considerably higher temperature still is desirable. The further rise of temperature possible in actual working is limited, however, by the fact that at a not very high temperature decomposition of the coal begins, with the production and evolution of gaseous combustible hydrocarbons; and also that in the presence of air at these temperatures (and in the ordinary operation of drying there must always be abundant air present) oxidation of the coal occurs at a very sensible rate. This oxidation is an action which gives out heat, and thus tends to raise the temperature still further, to accelerate itself, and possibly to lead to ignition of the coal;

but in addition to this both the evolution of gases from the coal and its oxidation mean the loss of combustible matter from it and consequent reduction of its calorific value. Driers should therefore always be chosen of adequate dimensions, so that they need not be pushed; and there should always be a good supply of air through the drier, to carry off the moisture at a comparatively low temperature without approaching saturation of the air as it leaves the drier.

In most of the forms of drier in use the drying agent is a furnace, the hot gases from which heat in the first place the metal shell in which the

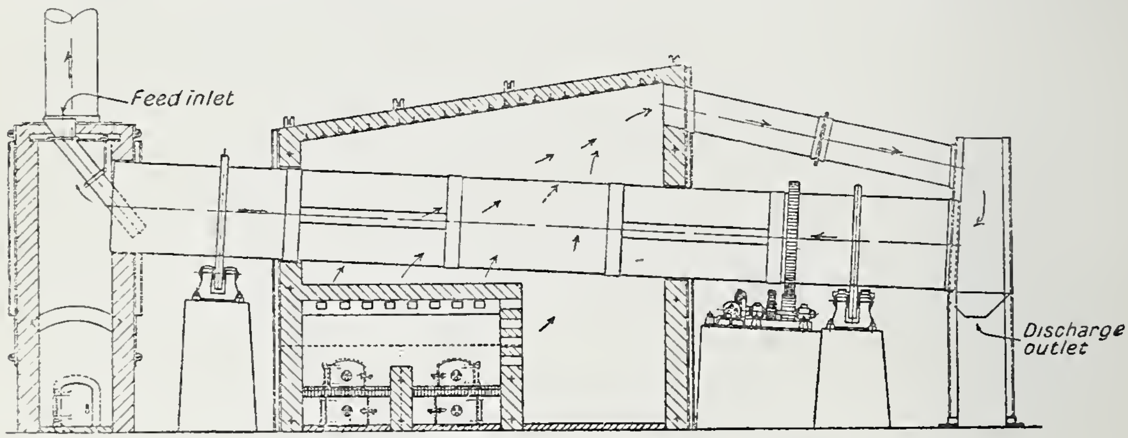

Fig. 5.—Indirect Fired Rotary Drier

coal to be dried is contained, and then pass directly over the coal itself, raising its temperature sufficiently for the evaporation of its moisture, and then carrying that moisture away in the form of vapour.

The drier made by the Fuller Company may be taken as illustrating the most usual form of drier. This is shown in Fig. 4, and its action is indicated diagrammatically in Fig. 5. It consists of a cylindrical shell slightly inclined to the horizontal, and fitted with rollers and gearing so that it can turn on its axis. The upper end opens into a brick housing surmounted by the exit stack for the waste gases. For the greater part of its length the shell is surrounded by the brick combustion chamber of the heating furnace, and its lower end enters a steel hood into the upper part of which a flue brings the flue gases from the furnace. The crushed coal is fed into the upper end of the shell by a feed spout which passes through the stack chamber, and is carried gradually down by longitudinal

shelves inside the shell, which lift the coal as the shell rotates and drop it through the current of ascending hot air, till it reaches the discharge outlet at the bottom. The hot gases from the furnace circulate around the shell, heating the contained coal; they then leave the combustion chamber, pass through the upper flue to the hood, travel over the hot coal through the whole length of the shell, and then leave, either directly through the stack, or, in some forms of drier, through a fan and a cyclone dust collector, where any fine fuel carried with them is deposited, to the open air.

The removal of moisture will be the more rapid, and the amount of coal dried per hour the greater, the higher the temperature of working; but this temperature must not be enough to heat the coal at any part of its course to a temperature at which it would begin to lose any part of its volatile constituents other than water, nor at which there would be any danger of rapid oxidation and possible consequent ignition of the coal. The regulation of the fire, and of the surplus air carried into the combustion chamber, must be so carried out as to secure this; and the uniformity and constancy of the supply of coal and the rate at which it passes through the drier are therefore of the highest importance. Any stoppage of the regular motion of the drier, too, without withdrawal of the fire, would mean the overheating of the now stationary coal, with almost certain decomposition and evolution of combustible gases, and possible ignition or explosion.

These driers are made in several sizes, ranging from 3 feet diameter and 20 feet long to $6\frac{1}{2}$ feet diameter and 42 feet long, and capable of drying from 2 to 25 tons per hour of coal containing anything below 10 per cent. of moisture. The power required runs from 2 h.p. for the smallest to 10 h.p. for the largest size, or from 1 h.p. hour to 0·4 h.p. hour per ton if the waste gases simply escape through the shaft; if a fan be used in connexion with the drier the power needed is in each case about $2\frac{1}{2}$ times as great. The coal required for the furnace may be taken at about 25 lbs. per ton, or between 1 and $1\frac{1}{2}$ per cent. of the coal dried.

The drier furnace may itself be fed with pulverised fuel; but owing to the small amount of firing required, and the large amount of excess air

that is necessary, the advantage of pulverised fuel is not great, and hand firing is more usual.

The Ruggles-Coles drier differs from the Fuller in that it consists of two concentric cylinders, and the path of the coal is in the annulus between the two. The coal is continually turned over as the drier rotates, by longitudinal ribs on the inside of the outer cylinder, and gradually traverses the length of the drier because of the slight inclination at which it is set. At the upper end the inner cylinder projects beyond the other and forms the flue of the drier-fire. The flue gases heat the whole length of the inner cylinder and then return through the annulus in contact with the coal to the shaft at the upper end.

Experiments are now being conducted with a drier in which gases from the combustion chamber of the boiler act as the drying agent. The gases are diluted with air till their temperature is reduced to the safety-point, though still above the temperature at which the gases in the usual drier come into actual contact with the coal. They pass over the coal in a rotary drier of much smaller dimensions than the present form, and are then returned to the combustion chamber. The capacity of the drier is thus greatly increased in comparison with its size; whilst any dust or combustible products of initial decomposition of the coal, due to the rapidity of the gas current or the high temperature used, are not lost, but are completely burnt in the combustion chamber.

It would seem economical to use, in drying the coal, the waste gases on their way to the stack; and this sound principle has been made by the Underfeed Stoker Company the basis of their "USCO" gravity drier. This consists of a vertical cylinder containing two concentric vertical stacks of circular louvres. The downward slope of the louvre plates of the outer stack is inwards towards the centre; that of the louvre plates of the inner stack is outwards. A piece of coal falling on the uppermost outer louvre is thus deflected inwards and falls upon a lower plate of the inner stack, which in turn directs it so that it falls upon a lower plate still of the outer stack, and it continues this interrupted zigzag path till it reaches the bottom. The connexion to the outlet of the coal bunker, which is immediately above the drier, opens out downwards conically, and the

conical louvred top of the inner stack of louvres projects into this. Coal falling from the bunker is thus projected centrifugally outward, and follows a delayed and broken path through the drier till it reaches the bottom, where a corresponding inverted cone collects it into the pipe which leads it directly into the pulveriser: there is thus no "dry coal bin" in the installation. Air from any convenient point in the flues is drawn out by a fan and piped to the drier, which it enters at one side close to the bottom, and after passing through the drier leaves it at the side, close to the top, and is taken back again into the flue. The period during which the falling coal is in contact with the hot gas is sufficient to reduce its moisture-content by 5 or 6 per cent., which is what is aimed at. The temperature of the gases entering the drier is not over 300° F., and they leave at any temperature high enough to ensure that they are well over the dew-point, so that there is no danger of any deposition of condensed water from them. A very rough diagrammatic sketch of this drier is shown in the section of the boiler-house at Vitry (Fig. 49, p. 134). A drier capable of drying 6 tons of coal per hour has a vertical height, in the cylindrical portion, of 18 feet and an outside diameter of 8 feet.

Not only does such a drier save the cost of installation and the operating cost of a separate fire, but it requires no mechanism nor power to drive it; and the power needed for the fan is probably not greater than that needed for the fan in those forms of inclined drier which use one. The danger of overheating which is present in all forms of fire-heated driers is non-existent, and the risk of fire is correspondingly lessened. Variation in the rate of supply of hot gases, to meet the needs of coals of different moisture-content, can be effected by varying the speed of the fan.

The writer understands that this drier is now being substituted, wholly or partially, at the Lakeside Station in Milwaukee, for the rotary driers originally installed there.

In all forms of drier in which the gases from the combustion of coal are used for drying it is to be remembered that these gases may themselves contain as much as 5 or 6 per cent. of water vapour, the amount of this being less, of course, in proportion to the amount of excess air with which the true products of combustion are mingled. (This is a reason for

preferring coke to coal as the fuel for a drier-fire, where such a fire is used.) The coal leaving the drier has the interstices between the pieces filled with this air, which when it cools to the ordinary temperature will deposit some of its moisture. The amount of this entangled air, and the amount of moisture so deposited, is extremely small; but it is from this point of view an advantage that the coal should go warm to the pulveriser, so that the moisture-containing air is disseminated through the relatively large volume of air entering the pulveriser, and the moisture carried off as vapour, before it has had time to cool far enough to deposit its moisture.

PULVERISING

From the driers the coal is either delivered directly to the pulverising mill, or it is elevated into a storage bin which can deliver it to the mill. Pulverising is of course the basic or fundamental operation of the plant, and many different forms of mill have been devised to effect it. In the cement industry, ball or tube mills were originally used. These are expensive to install and to work, and occupy a large space; and whether they grind the coal as finely as the modern high-speed mills is not perhaps very clear. But as they work at a low speed, and have large working surfaces, their wear and tear is comparatively slight, and they work steadily and uniformly, and need little skilled attention.

They have been much used in Germany, and are typified by the Solo Mill of Polysius, which is shown in Fig. 8 and in section in Fig. 6. It is a rotating cylinder of steel plates, about 36 feet long, and divided into two chambers, in which the coarse and fine grinding respectively are carried out. The first chamber is lined with hardened steel plates and is filled to the level shown with steel balls. The second or fine chamber has a silica lining and is filled with flints. The material in the first chamber is gradually worked forward and finds its way out by the openings at the front end, falling upon the sieve which occupies the middle of the annular space around the grinding chamber. The finer portions pass this sieve and are carried forward by the outer spiral and delivered into the second chamber as indicated; the coarser portions are carried backward by the

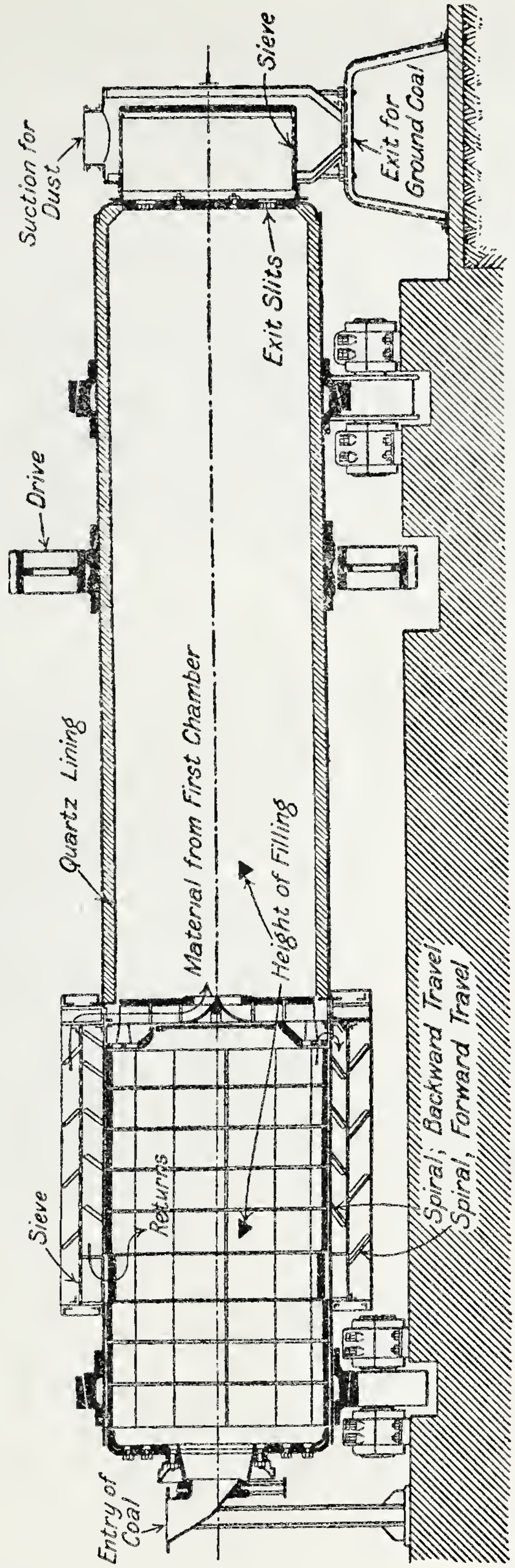

Fig. 6.—Polysius Solo Mill—Section

inner spiral and returned to the first chamber for further grinding. The fine stuff is gradually worked along the second chamber and passes out through slits into the stationary chamber at the end. The bottom of this is furnished with a sieve to keep back any accidental coarse particles, and the ground coal falls into a receptacle below. The regulation of the fineness of the ultimate product is effected, not by sieves, but by regulating the rate of feed and the speed of rotation. The necessary speed depends on the nature of the coal and on the degree of fineness desired : as a rule it will be from 20 to 27 revolutions per minute.

The mill is extremely simple and, being thoroughly closed, is very clean in its working. All the gearing is outside, so that wear is very slight, and the inside is easily accessible for any repair, which should, however, very seldom be needed.

THE FULLER-LEHIGH PULVERISER MILL

This mill is shown in Fig. 7. All the working parts are driven from the central shaft, actuated from the driving pulley at the bottom of the mill. The feeder is either a screw conveyor, as shown in the figure, or a rocker with adjustable stroke, which carries the coal from the hopper, fed from the storage bin. The coal falls into the grinding ring, which is fixed, and is ground by four heavy steel balls which are carried around the ring by four pushers attached to arms on a yoke keyed to the shaft. This yoke, and the mode of attachment of the pushers, are seen in Figs. 9 and 10. The yoke also carries the vertical and inclined blades of the separating fan, which by its rotation raises the fine dust into the space above the grinding ring. The outer wall of this space is a "protecting screen" of metal, with square or rectangular openings, outside of which is the "finishing screen" of wire gauze, the openings in which may vary in different mills from 4 to 55 per lineal inch. Below the grinding ring is the discharge fan, also keyed to the central shaft. This draws a current of air through the mill, which carries the suspended fine particles through the screens down into the fan housing, whence they are discharged through the discharge spout.

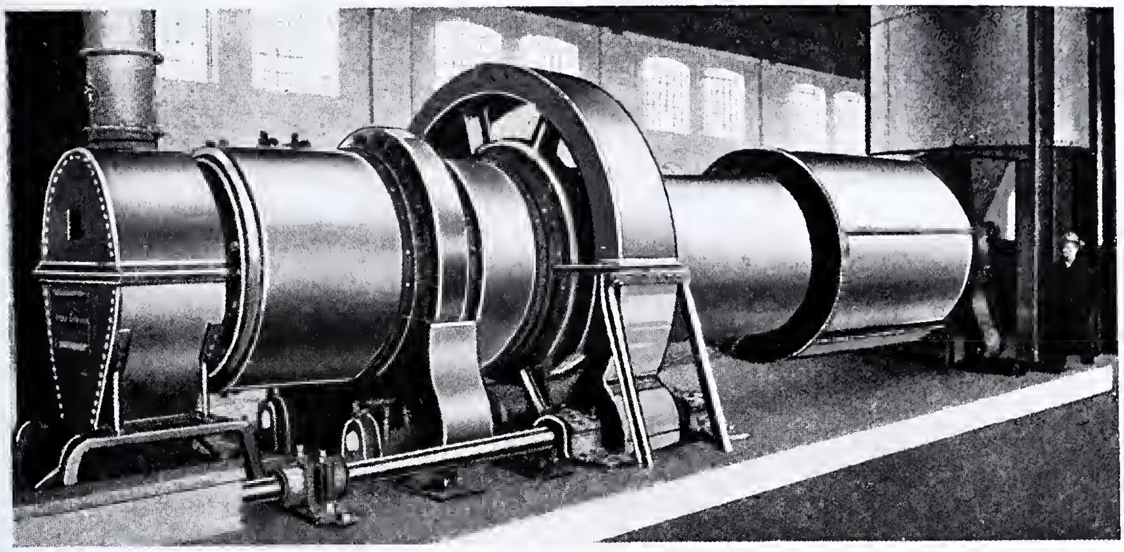

Fig. 8.—Polysius Solo Mill

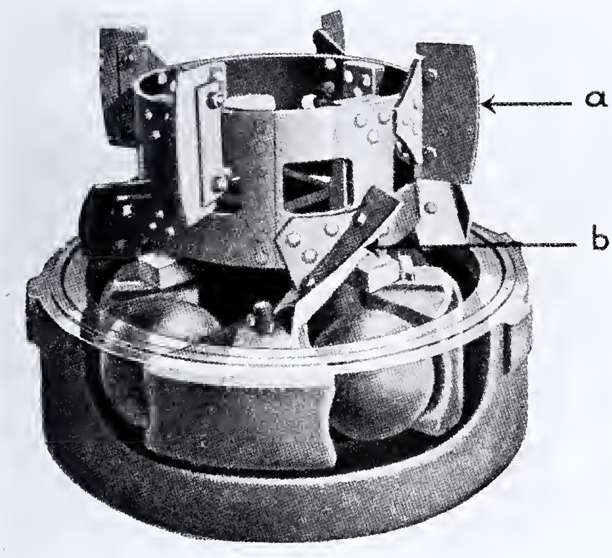

Fig. 9.

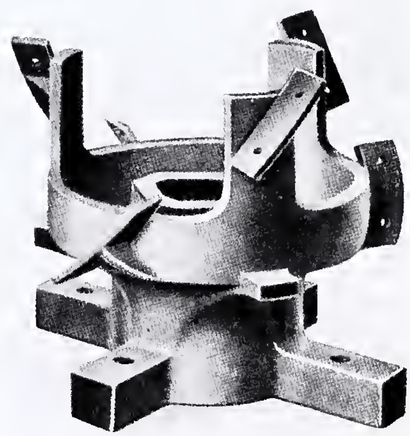

Fig. 10.

Fuller Mill—Details

It will be seen that the step cones from which the feeder is driven permit regulation of the rate of feed; and the hopper is provided with a slide so that the operator can increase or decrease the rate at which the material enters the hopper. The material falls in a continuous stream

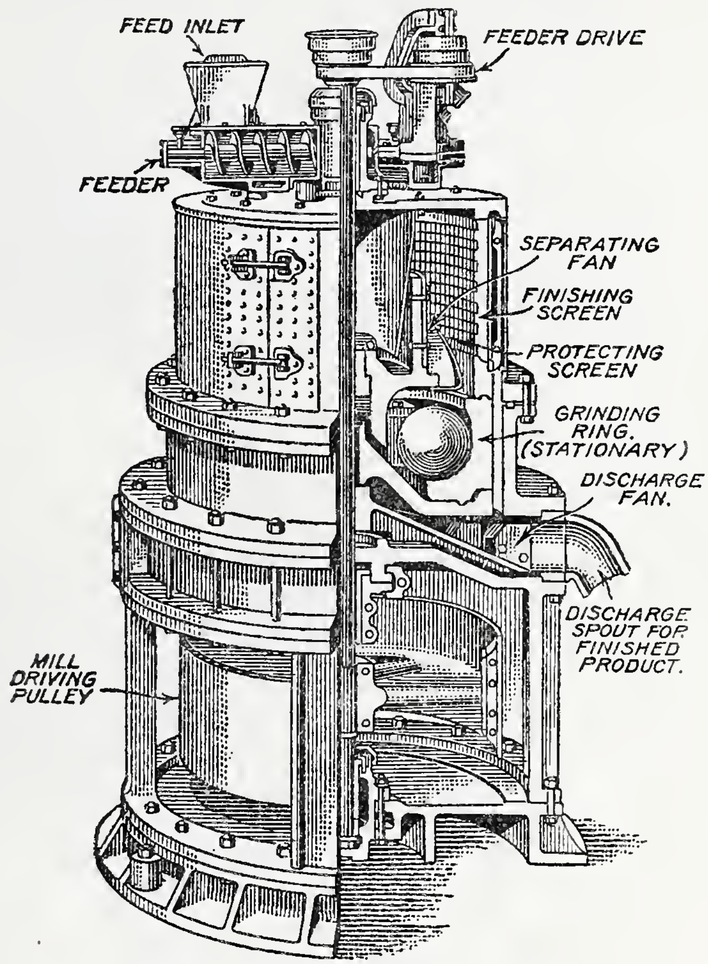

FIG. 7.—FULLER MILL—DIAGRAM

between the balls and the grinding ring and is pulverised in one operation. The crushing force is all exerted on the limited amount of material present at any one moment, and thus operates effectively and economically; and the material is automatically carried up out of the ring as soon as it has reached the requisite fineness. The air drawn through the pulveriser keeps the temperature from rising, carries off moisture (unless it be very moist) and keeps the screens clean. It will be noted that the finest

screens used are much coarser in the mesh than corresponds with the fineness of the product: they are only protective, and the separation is entirely effected by the air current.

The Fuller mills are made in four sizes, taking coal from $\frac{3}{4}$ inch to $1\frac{1}{4}$ inch, giving outputs of $\frac{1}{2}$ to 10 tons per hour of pulverised fuel, 95 per

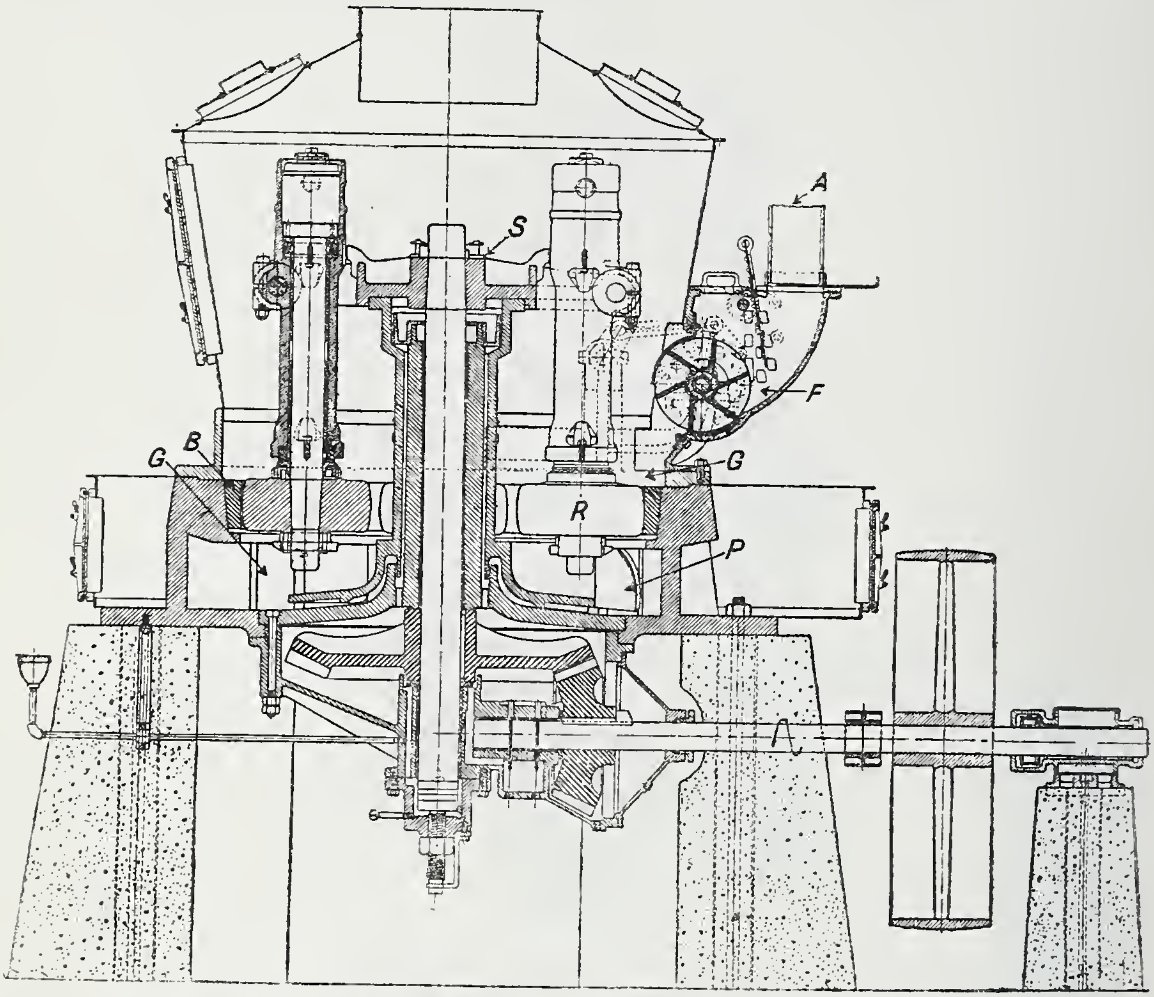

Fig. 11.—Cross-Section of Raymond Four-Roller Mill

cent. of which will pass a 100-mesh sieve, having speeds of 300 to 130 revolutions per minute, and requiring 10 to 100 h.p. to drive them, or from 17 to 10 h.p. hours per ton.

The wearing parts of the mill are the balls, pushers, grinding ring and screen. The Fuller Company consider that when the mill is used with bituminous coals or lignites the operating life of the balls, pushers

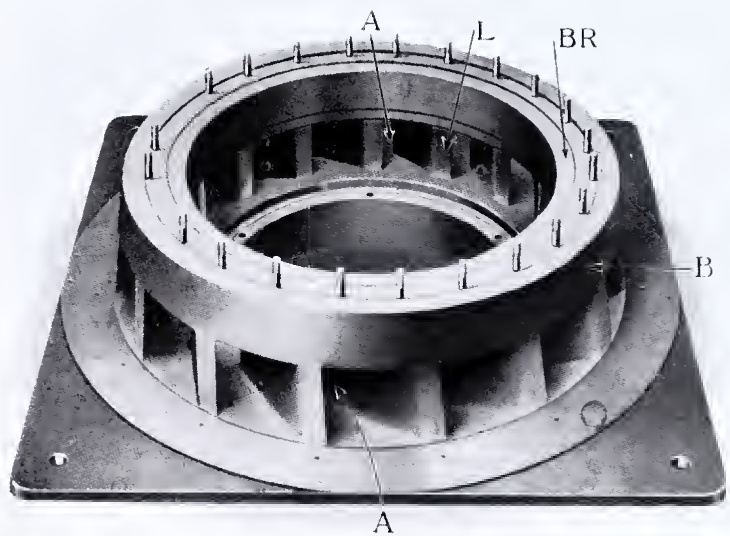

Fig. 12.—Base, with Air Ports and Bull Ring

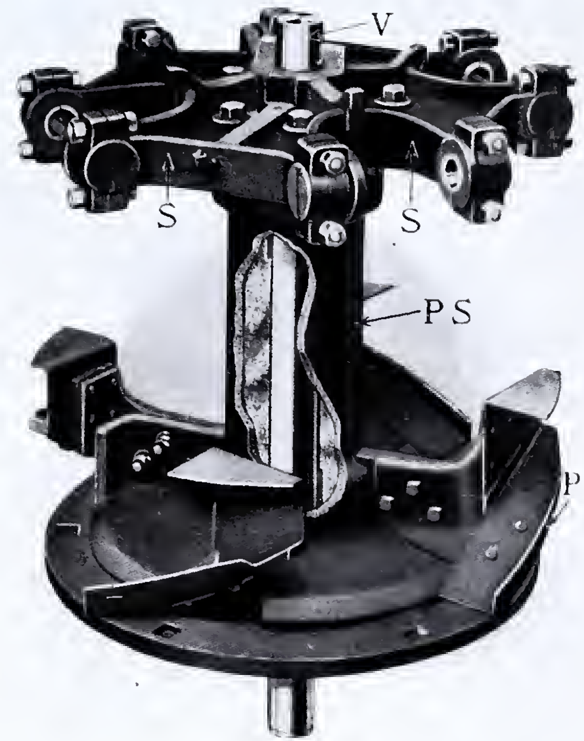

Fig. 13.—Main Shaft, with Support for Plough and Spider

and screens is about 3000 mill-hours, and that of the grinding ring 24,000 (the smallest mill gives higher figures); thus the four mills will produce respectively about 6000, 10,000, 13,000 and 19,000 tons of pulverised fuel before balls, pushers and screens will need replacement, and eight times those amounts before the grinding ring will need it. This long life is due to the mill never working empty, so that there is always a cushion of coal between the hard steel surfaces.

The Raymond pulveriser is shown in Fig. 11. The coal enters from the spout through the automatic feeding mechanism *F*, which delivers it into the grinding chambers *G*. The rotating manganese steel ploughs *P* throw it up from the chamber floor between the rollers *R* and the pulverising ring *B*. Each roller is carried in a sleeve or journal, which is pivotally suspended from an arm of the "spider" *S*; so that during rotation centrifugal action forces it outwards, and grinds the material between the roller and the ring. An exhaust fan above the mill draws through the mill a stream of air, which enters by tangential openings around the base of the grinding chamber, and carries the pulverised material up with it. The finer particles are carried on into a cyclone collector; the coarser material falls back and is ground further. The air ports in the base, the main shaft with the support for the ploughs and spider, and the mode of attachment of the rollers are shown in Figs. 12, 13 and 14, and the whole arrangement of mill, separator, fan and collector in Fig. 16.

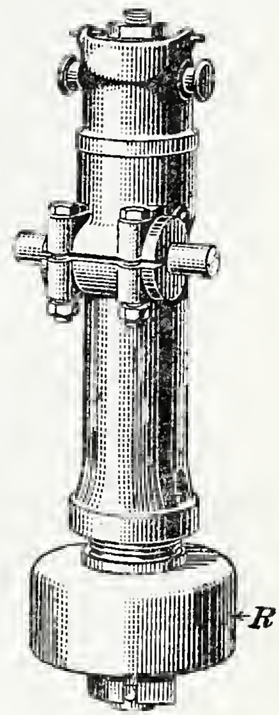

Fig. 14
Roller Journal, Raymond Mill

In this, as in the Fuller mill, efficiency depends upon the regulation of the feeding mechanism, so as to keep the mill always supplied and thus prevent the metal surfaces from working on one another, and yet to avoid choking it. The mills are made in different sizes, with from two to six rollers. The maximum speed of the main shaft is below 120 revolutions per minute. All the moving parts are lubricated; the operation of

lubricating, which should be carried out once a day, requires about twenty minutes. The coal fed to the mill may be anything between $\frac{1}{4}$ inch and $1\frac{1}{2}$ inch, and about 95 per cent. of the finished product will pass a 100-mesh sieve. The power needed ranges from 40 h.p. for the

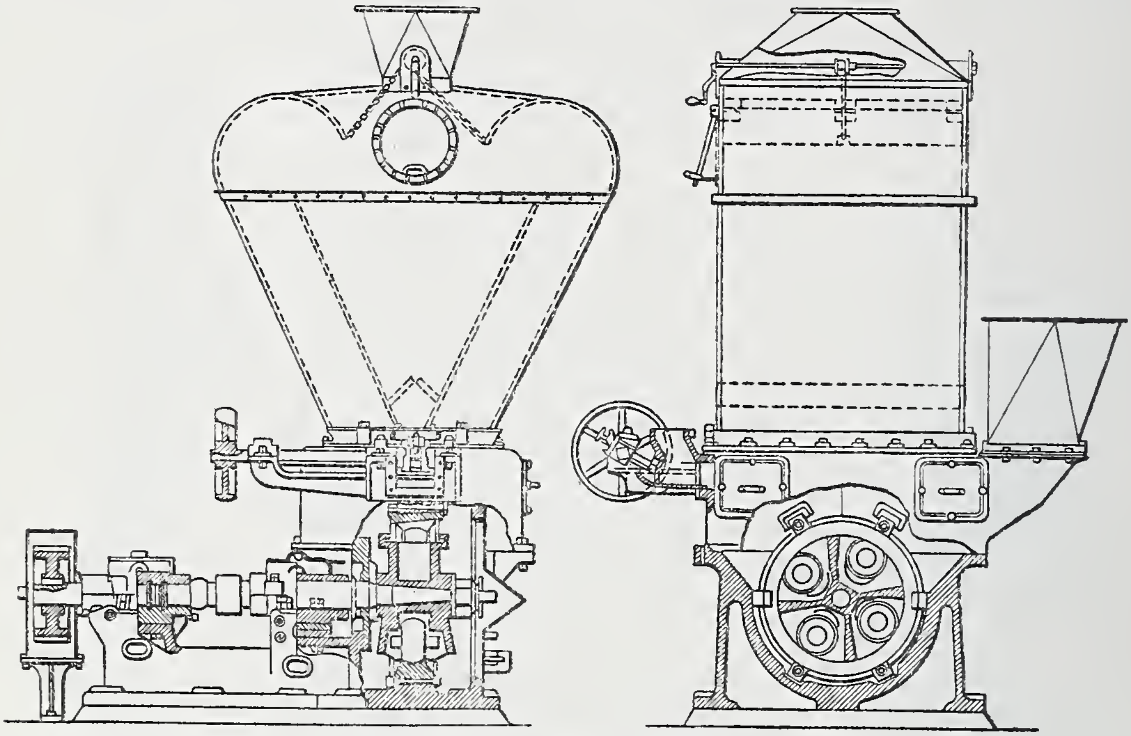

Fig. 15.—Bonnot Pulveriser

2-roller mill producing 2 tons per hour to 105 h.p. for the 6-roller mill producing $6\frac{1}{4}$ tons per hour : 20 to 17 h.p. hours per ton.

In the Bonnot pulveriser, seen in Fig. 15, the work is also done by rollers actuated by centrifugal force ; but here the grinding ring is vertical instead of horizontal. The horizontal rollers are carried in a driver mounted on a horizontal shaft, and are constrained to move in radial slots in the driver frame, which is so shaped as to guide the coal in front of the rollers. The ground product is thrown up into the bottom of the separator, where it is caught by a current of air drawn in by an exhaust fan above the separator. The fine particles are carried on through the fan ; the coarser ones fall back between the interior flue plates, shown by the double dotted lines, into the mill. The flue plates are hinged at the bottom so that the angle between them may be altered and products of

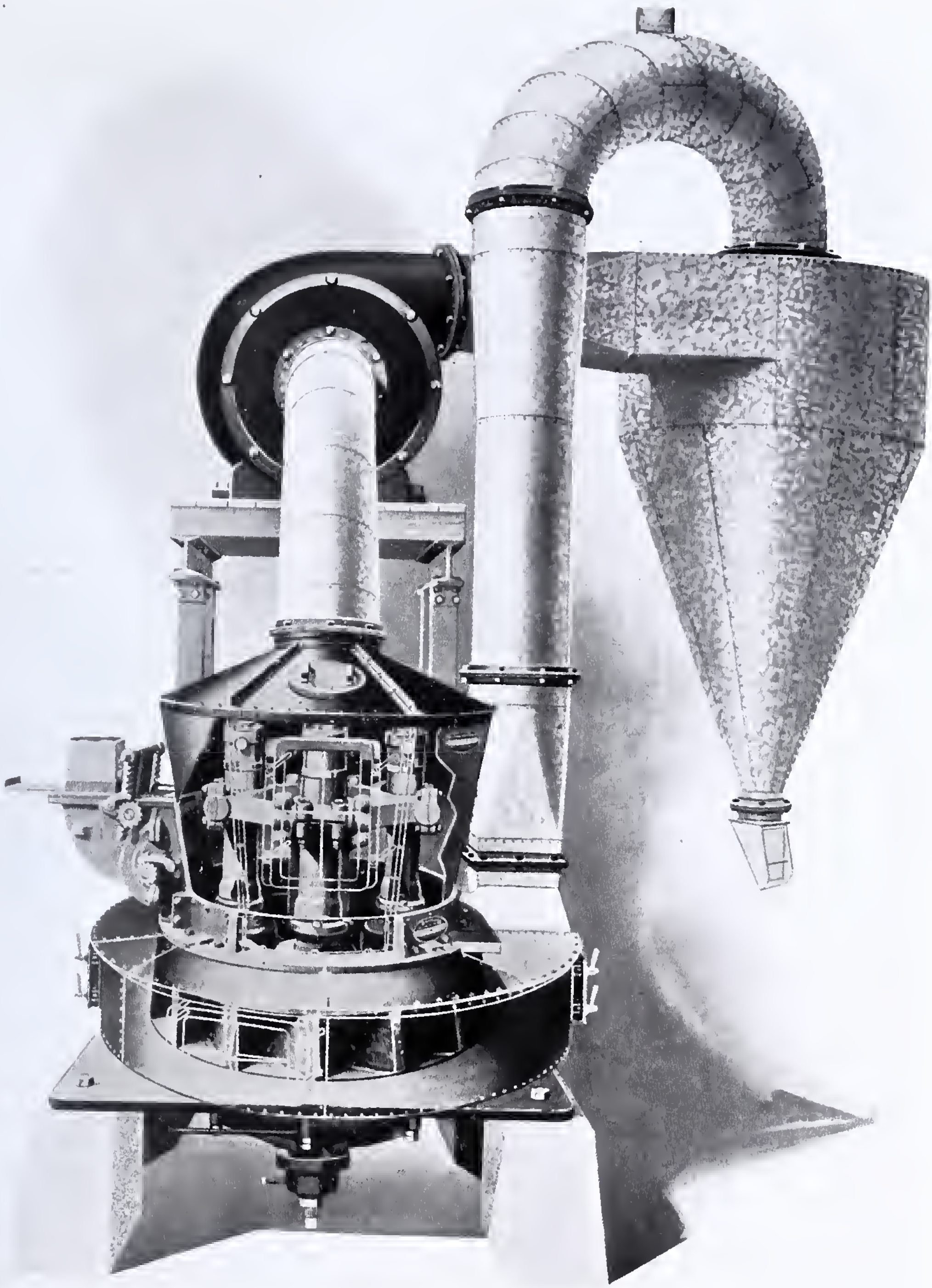

FIG. 16.—RAYMOND MILL, WITH SEPARATOR AND COLLECTOR

varying fineness obtained. The farther the plates are from parallelism with the outer walls, and the nearer to the vertical, the coarser will be the product carried on by the air current. The pulverised fuel passes the fan, to a cyclone collector, from the top of which the air returns to the mill.

Bonnot mills are made in three sizes, with capacities of 2500, 5000 and 10,000 lbs. of coal per hour.

The Sturtevant ring-roll mill resembles the Bonnot mill in so far as the work is done by horizontal rolls against a vertical ring ; but it differs essentially from it in construction and working. The grinding ring here is driven from the motor, and the three rolls, which with the sleeves supporting them are capable of revolution on fixed axles, are driven by friction from the ring. Instead of being held against the ring by centrifugal force, the rolls in this mill are pressed outwards by a strong spring. The mill is seen in section, with the driving mechanism, in Fig. 19, and the arrangement of the levers on which the rolls work, with the balanced washer through which pressure from the spring is equally distributed among the three, is shown on a larger scale in Fig. 19, which also shows the method of lubrication of the bearings. Fig. 20 shows the attachment of the rolls to the heavy door of the mill, which can be opened so as to give access to the moving parts. The coal is fed through the hopper ; the unground portions are held against the ring by centrifugal force, and are ground between the rolls and the ring. The finely ground product escapes at both sides of the ring (Fig. 21) and escapes at the bottom of the mill. As long as coal is supplied, rolls and ring are never in contact with one another, but are separated by a layer of coal, so that the wear is very small. The ring and the rolls are the only parts of the mill that need renewal. The pressure which the spring exerts is adjusted by a central screw on the outside of the door, and each roll can be made to press outwards against the ring or the intervening coal, with a pressure of 20,000 to 40,000 lbs. ; and of course when the mill is running empty the rolls can be held away from the ring so that there is no wear between them. The product of the mill is separated by air separation as in the other forms of mill, the fine portion being carried on into the installation and the coarser portion returned to the mill. The No. 2 mill

turns out 5 tons of coal per hour, ground so that 95 per cent. passes a 100-mesh and 85 per cent. passes a 200-mesh sieve. It requires for this 35 to 40 b.h.p., whilst the elevator requires 10 b.h.p., and the separator 8 b.h.p., a total of 11 to 12 h.p. hours per ton.

In the "turbo-pulveriser" of the Powdered Fuel Plant Co. Ltd. the coal is broken up by blows instead of by grinding. A number of discs, carrying loaded blades at their periphery, are carried on a horizontal shaft, and are surrounded by a cylindrical envelope divided by partitions into as many compartments as there are discs on the shaft. Coal is fed into the pulveriser by a distributor at one end, and at the other end, working in a separate compartment, is a fan, which draws in a current of air from the distributor end through an adjustable inlet. By this current of air the coal is carried successively through the compartments and exposed to the action of the blades, and ultimately passes through the fan and is driven forward to the burner. The pulveriser is shown in Fig. 22.

In this apparatus the fineness of the pulverisation is determined by the rapidity of the drift of the coal through the apparatus, which in turn depends upon the rate of admission of air. There is a second adjustable air inlet between the pulveriser and the fan, and by making use of this practically the whole of the air needed to burn the coal can, if desired, be mixed with the coal in the fan and delivered at the burner.

The pulveriser is made in five sizes, dealing normally with 550 to 5000 lbs. of coal hourly, working at speeds of 2100 revolutions per minute in the smallest, and 1450 in the largest size, and requiring from 10 to 65 h.p., or from 40 to 29 h.p. hours per ton. They will run on 50 per cent. of normal load and can be pushed considerably beyond it without sensible loss of efficiency.

There is usually no need for a drier to be used with these machines, as there are no storage bins, and usually the transport line is very short, as each pulveriser is installed close to the furnace which it feeds; but if the coal used be very wet there is a loss of efficiency, both through the extra power needed to put through a given weight of coal and the extra weight of coal to be put through, and also because the coal is not

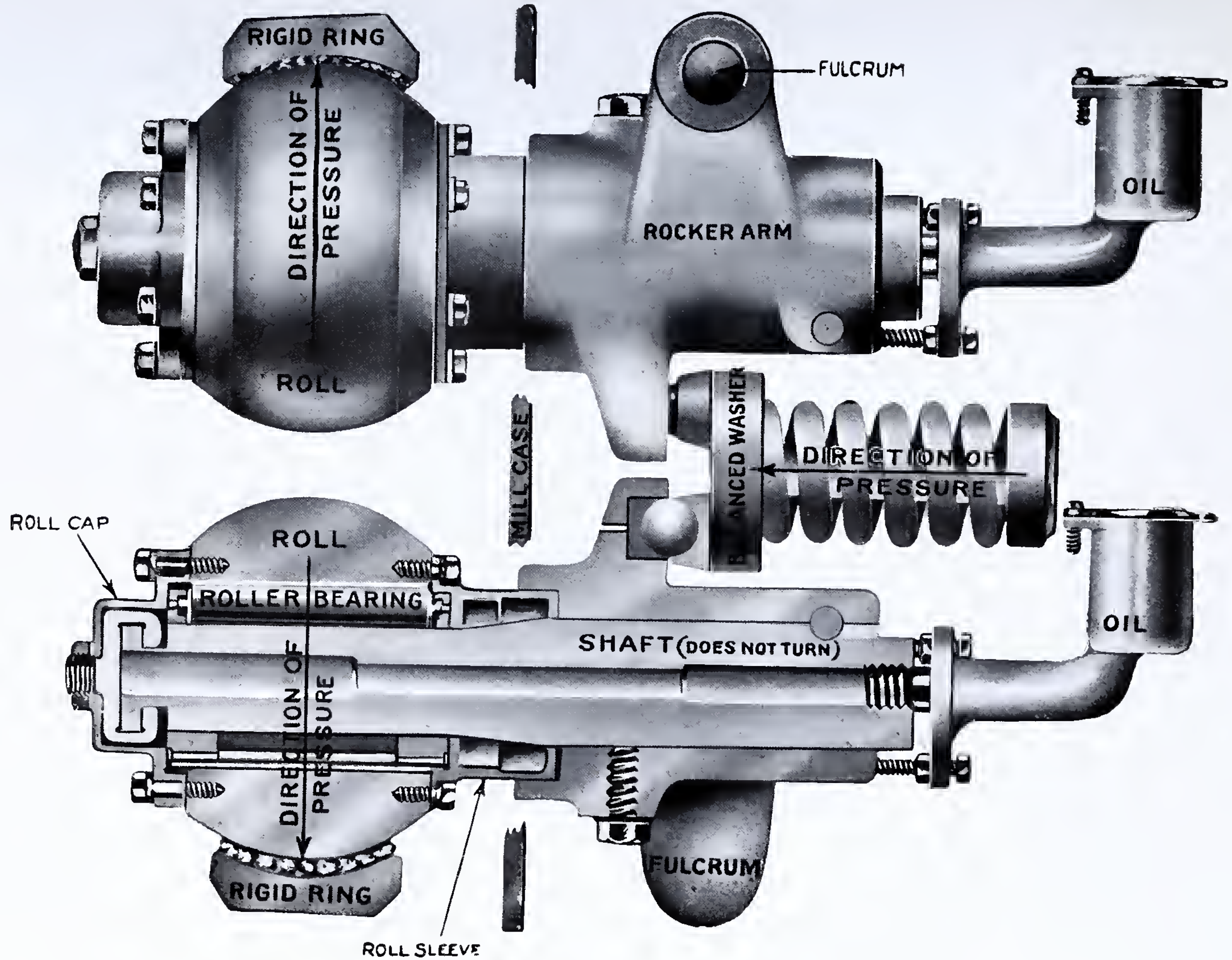

Fig. 17.—Sturtevant Mill—Details

pulverised so finely. The apparatus will deal with coal up to 1 inch in size ; but its work is more satisfactory if the largest pieces fed are not more than $\frac{5}{8}$-inch cube.

Naturally, at the high speed of working, the wear on the blades is

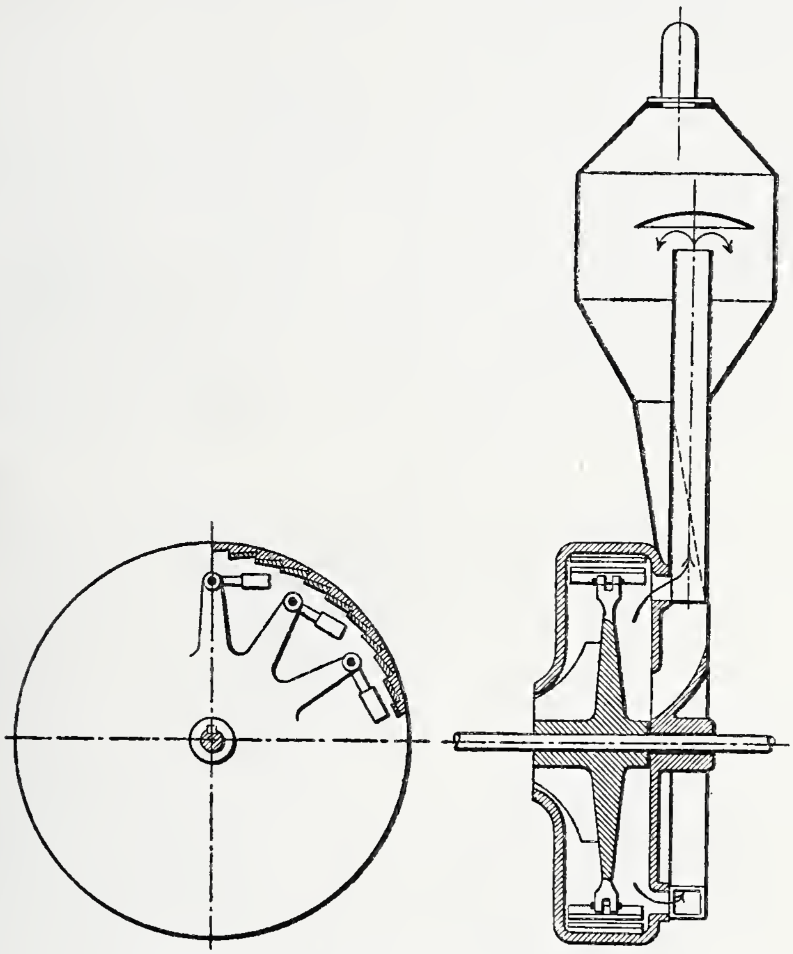

Fig. 18.—Bettington Pulveriser

considerable, and they need replacement, with average coal, about every four months. This replacement is readily and easily effected.

The liners also experience considerable wear and need replacing about once a year ; and the fan, through which the whole of the powdered coal and the air go, will probably last not longer than two and a quarter years, when it, too, needs to be replaced (see p. 152).

The Bettington mill, designed for use with the Bettington boiler, is also a percussion pulveriser. It is shown diagrammatically in Fig. 18.

It consists of a simple cylinder containing the hammers, which are pivoted on the ends of rotating arms. The whole of the air needed for combustion (previously heated by the flue gases) passes through the pulveriser, and carries with it the powdered coal into a separator, from which the fine particles go on to the burner, whilst the coarser stuff falls back again into the mill. The grinding is probably not so fine as in the other mills; the speed of rotation is about 1400 revolutions per minute, and the energy needed is from 35 to 38 h.p. hours per ton, including that needed for the air supply.

From what has already been said, it is clear that the finer the coal is pulverised the more intimate can the mixture of coal and air for combustion be made, the greater is the surface of contact in comparison with the bulk and weight of the coal, the more easily will ignition occur, the more rapid will be the combustion, and the more easily will it be made complete. Accordingly, all the makers of pulverising machinery have aimed at extreme fineness, and it has become a sort of accepted standard that 95 per cent. of the milled product should pass a 100-mesh, and about 85 per cent. should pass a 200-mesh sieve. It seems as though the necessary fineness should bear some relation, however, to the nature of the coal, and that a soft coal, low in ash and high in volatile matters, might be expected to burn completely in a coarser condition than a harder, more anthracitic coal; and as the power needed for grinding (and the grinding takes about 80 or 85 per cent. of the total power used in the installation) increases rapidly with the fineness of the grinding, it would seem desirable to ascertain by experiment in any installation how far it is necessary to go in this direction with the coal regularly used. In the Bureau of Mines tests of the Oneida Street plant, four tests were run with coal ground less finely than usual, having in fact the mechanical condition shown below:

	Passed through Screen		
Test No.	40-mesh	100-mesh	200-mesh
32 . . .	99·2	93·2	67·0
33 . . .	99·2	93·1	70·1
34 . . .	98·9	90·8	65·5
35 . . .	98·0	88·6	64·0

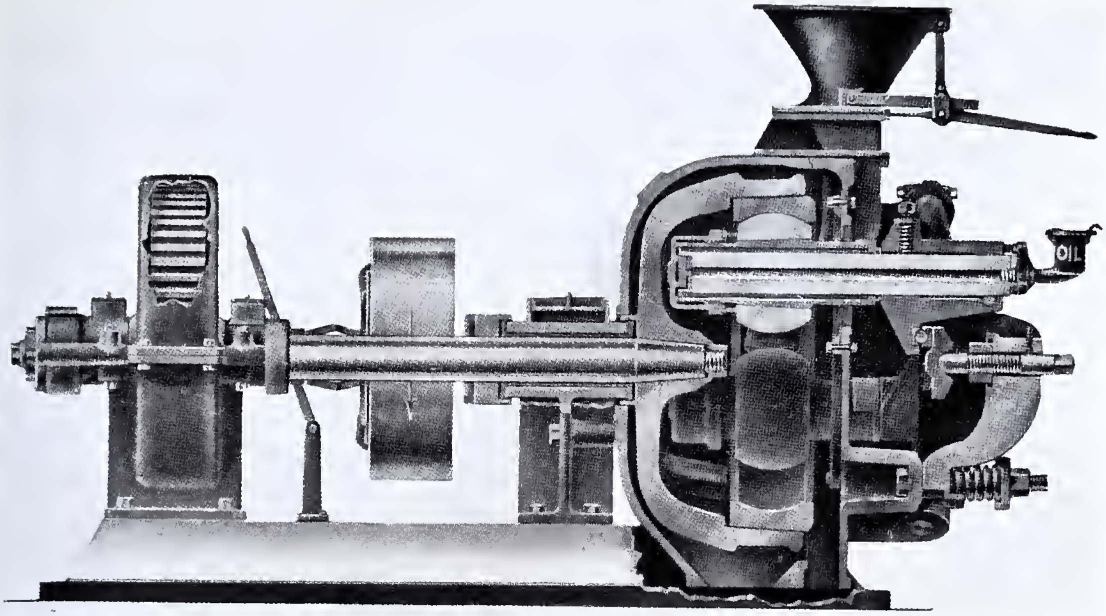

Fig. 19.—Sturtevant Mill—Section

Fig. 20.—Sturtevant Mill—Open

The report says: "The results of these tests seem to indicate that it is not necessary to pulverise the coal to the extreme fineness of 85 per cent. through the 200-mesh screen in order to get good combustion and good efficiency. The completeness of combustion seems to be more a matter of proper furnace and burner design and the right way of supplying air than the fineness of the coal. The losses due to coarseness of coal would be shown by the greater percentage of carbon in the refuse. The average loss due to this cause for the four tests with the coarser coal is 0·7 per cent. The average of this loss for the previous four tests is 0·6 per cent. The average of the efficiencies is very nearly the same (81·7 for the four with coarser coal, 81·9 for the previous four). The ability to burn coarser coal means increased capacity of the pulverising mills and decreased cost of coal preparation." How far this is the case is shown by the following figures, extracted from a Table given in the *Transactions of the American Society of Mechanical Engineers*, vol. xxxvi., showing the energy needed to pulverise the same coal to different degrees of fineness in Raymond pulverisers :—

Capacity of mill tons per hour	Per cent. through 100-mesh	Per cent. through 200-mesh	H.P. hours per ton	Capacity of mill tons per hour	Per cent. through 100-mesh	Per cent. through 200-mesh	H.P. hours per ton
2 .	95	82	22·5	10 .	95	82	17·0
2 .	99	95	30·0	10 .	99	95	28·0
3 .	95	82	20·0	25 .	95	82	17·0
3 .	99	95	28·0	25 .	99	95	28·0

and Mr J. S. Atkinson, in a paper read lately before the Bradford Engineering Society, gives the following results obtained with a turbo-pulveriser :—

Output of Coal per hour	Horse-Power	Fineness	
		Through 100-mesh sieve	Through 200-mesh sieve
		Per cent.	Per cent.
1980 lbs. . .	42·5	96	82
2700 lbs. . .	37·0	94	75

Expressed in terms of 1000 lbs. of coal per hour, the power required is 21·46 and 13·7 h.p. respectively for the outputs mentioned in the foregoing table.

The mechanical action of pulverisation tends of course to raise the temperature of the coal; but the extent to which this actually occurs is very small. Fifteen h.p. hours for a ton of coal is a reasonable figure for one of the larger mills. This is equivalent to about 37,500 B.Th.U., which works out at nearly 17 B.Th.U. per lb. of coal; and if we assume the specific heat of coal to be 0·25, this amount of heat would raise its temperature by 68° F. Not the whole of the energy, however, goes to raise the temperature of the coal; some portion of it is spent in doing molecular work in the separation of the particles, and some of the heat produced by the other portion is dissipated by conduction through the structure of the mill; so that the possible rise of temperature must be considerably under 68°. In one test with a Raymond pulveriser, coal entering the mill at 75° F. left it at 105° F.; and in another, where the coal went into the mill direct from the drier at 238° F., it left the mill at 170° F., having lost more heat to the mill than the grinding had produced. Any idea, therefore, of dangerous heating of the coal through pulverisation may be dismissed.

In some forms of mill the separation of the finished finely pulverised material from the coarser particles which need further grinding is effected by sifting through gauze screens; in others, it is done entirely by suspension in air, an application of Stokes's law (p. 179) connecting the speed of fall through a resisting medium with the size of the falling particle. Neither system is necessarily superior to the other in all cases; the construction of the mill and the other circumstances of the installation need to be considered in discussing the question. The disadvantages of sieves are chiefly two: wear, through the constant abrading effect of the fine coal falling upon and passing through them, and clogging. Wear can be greatly reduced by a guard sieve of larger mesh placed within or in front of the separating sieve. Clogging is much more likely to occur, of course, if the coal is damp; where sieves are used, therefore, a drier should form part of the installation, and the mill should be plentifully

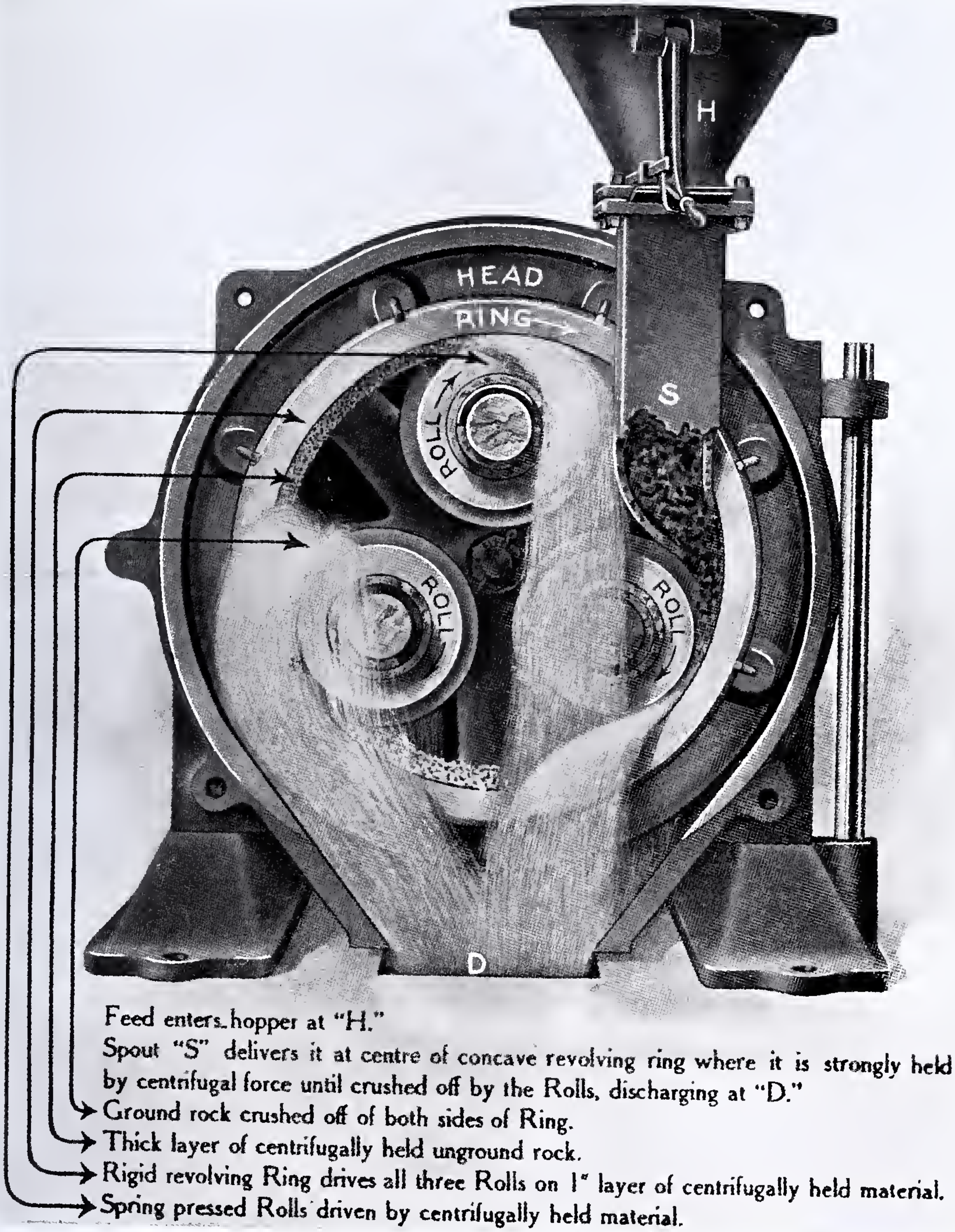

Fig. 21.—Sturtevant Ring-Roll Mill

supplied with air to prevent the condensation of moisture. In general, it may be said that slow-speed mills of the ball mill type are better adapted for sieve separation, and high-speed mills for air separation, and that air separation is always desirable for unit installations, where driers are hardly ever used, and where the fuel is delivered direct from the pulveriser to the burner.

The relative advantages of slow-speed and high-speed mills, too, can only be decided with regard to the requirements of the installation as a whole. Ball mills are more costly, take up more room and need more power than high-speed mills; but they need less attention and cost less for repairs and upkeep. They are steady and continuous in their work, but not elastic, and high-speed mills will always be more suitable where the load on the installation is variable, or where powdered fuel firing has the character of a reserve, or may be used as an auxiliary for peak loads.

The choice of a mill, too, may depend on the required fineness of the coal for firing. If burners should be devised, or furnace design altered, so as to burn coarser material satisfactorily and efficiently, the relative advantages of different mills might be altered: one less efficient than another in producing extremely fine material might be more efficient or more economical in producing coarser stuff.

In drawing conclusions from existing installations it has always to be borne in mind that the data derived from one industry will not necessarily hold for another; that the maintenance and repairs of mills in the cement industry, for example, may be more or less costly than those in a power installation; and further, that in considering a whole installation, advantages or defects which are really due to one part of the system may apparently spring from, and may be erroneously ascribed to, another part.

Certain requirements must be made of any mill. First, it should be efficient; require the minimum expenditure of energy for the work done. Beyond that, it should be as simply constructed as possible; the working parts, and especially the grinding surfaces and those exposed to the continual passage of powdered fuel, should be made of material that will wear away but slowly; all parts, but especially all parts that call for

periodical renewal, should be readily accessible for cleaning or repair, and it should be possible to remove and replace the renewable parts readily and rapidly; the construction should be strong and all joints perfectly tight. Lack of tightness and escape of fine coal-dust into the air has been in the past the cause of fires and explosions, and both for this reason and for the sake of cleanliness and economy perfect tightness is very desirable. In this respect mills with air separation have an advantage, for during the whole of its passage through the mill, until it has reached the exit side of the separating fan, the material is in a space where the pressure is slightly below that of the atmosphere, so that leakage, if it occurs at all, is inward and not outward.

TRANSPORT

The pulverised coal from the mill is collected directly at the outlet of the mill, by means of an elevator working from the outlet, or by the use of the air current from the mill, in a storage bin; and from this it is transported to the furnace burners. The mode of transport depends upon the positions of the furnaces, upon the design of the installation, and upon the conditions under which the furnaces work; but in most installations transport is effected either by screw conveyors or by the use of compressed air.

The screw conveyor is the oldest method. The helix rotates in a dust-tight trough, into which the pulverised fuel is fed from the storage bin; the conveying pipe forms a continuation of the trough of the conveyor. This contrivance is mechanically very simple; it is easy to operate, continuous and steady in its action, inexpensive to maintain, and needs little attention. A 6-inch conveyor running at 50 revolutions per minute will deliver about 2·5 tons, at 100 revolutions per minute about 4 tons, per hour. The corresponding figures for a 12-inch conveyor are about 8 and 14 tons per hour. The power consumed is from 1 to 1·5 h.p. for each ton per hour, carried 250 feet. The screw conveyor can only transport material along a practically horizontal line, and hence must be combined with an elevator where any considerable change of

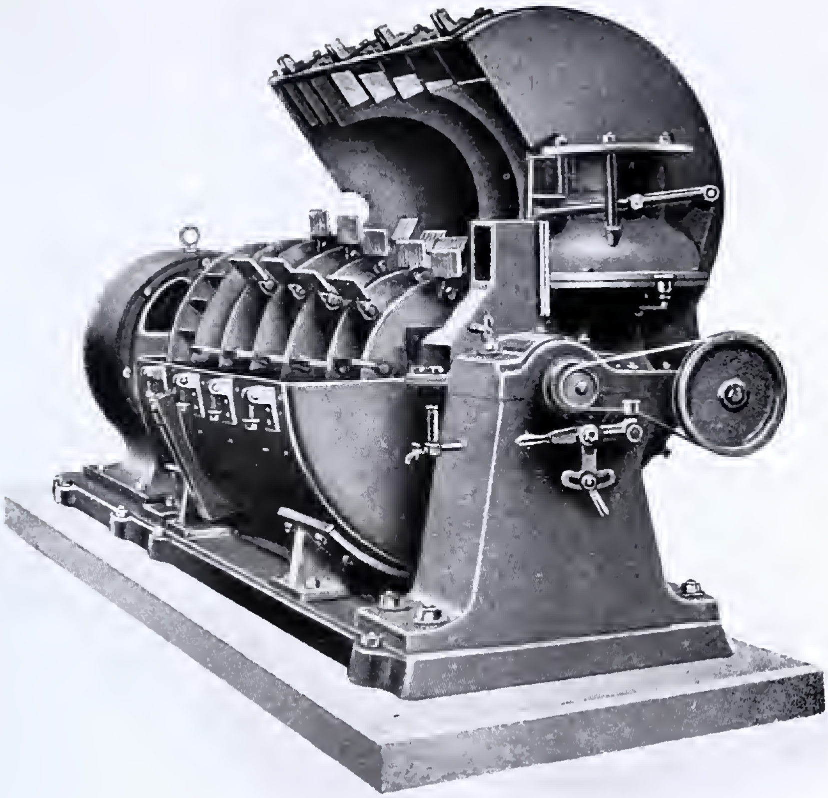

Fig. 22.—Turbo-Pulveriser

level occurs. Their housings must be as smooth as possible, and dryness of the coal is important, for fear of clogging and stoppages ; for the same reason they should not be allowed to remain full of material when at rest. In some instances the bottom of the thread, or axis, of the conveyor is tapered in the forward part, so as to deepen the thread, " so that after the screw has taken its bite the volume increases as a threadful advances, and the flow to the pipe is easy and free in consequence." In most cases screw conveyors will be used to deliver coal to storage bins supplying the burners at the furnaces or sections of the plant, and further conveyors to deliver from these bins to the burners ; but branches can be taken from the conveyor line to supply burners directly. The weight of screw conveyors and the consequent need of rigid supports for them are disadvantages, but they hold their own, in spite of this, for conveyance over level circuits and comparatively short distances. " Screw conveyors of 9 inch and 12 inch in diameter should not exceed 250 and 300 feet respectively, if the best results are to be expected. Where transmission lines of greater length are necessary they should be divided."

The transport of pulverised coal through pipes, whether by means of screw conveyors or by one of the " pneumatic " systems (but in a greater degree, perhaps, with these), is facilitated by the fact that, like most fine powders, fine coal " adsorbs " or attaches to its surface a quantity of air (or other gas with which it happens to be in contact). Cushmar and Coggeshall, quoted by Bancroft (*Applied Colloid Chemistry*, p. 21), found that a rock powder passing a 200-mesh sieve filled only 46 per cent. of the volume of the vessel which contained it and which it apparently filled completely, the remaining 54 per cent. being occupied by the air film which each particle carried around it. This air cushion around the particles made the powder flow like a liquid, the friction between contiguous particles or between the particles and the containing vessel being really that of air and not that of coal. So, in some experiments of the author's, the powder from a coal of specific gravity 1·27, ground so as to pass a 200-mesh sieve, when filled into a vessel was found to weigh 41 grams per 100 c.c. instead of 127—that is to say, it filled only 32·3 per cent of the volume of the vessel, the attached

and entangled air being 67·7 per cent., or more than twice the volume of the coal itself. The weight of a cubic foot of this dust would be a little over 25 lbs., whilst a cubic foot of the solid coal would be 80 lbs. Settlement of such dust in a bin would of course cause some increase in its density, and a corresponding squeezing out of some of the air; but under no circumstances likely to occur in the normal working of a powdered fuel installation would the volume of attached air be reduced below 50 per cent. of the total volume. Mann (*Gen. Elect. Review*, 1915, xviii. 922) says as the result of experience: "The weight of a cubic foot of (powdered) coal may be anything from 20 lbs. to 50 lbs. As coal lies on a feeder screw it will not reach 20 lbs. per cubic foot. When delivered by a conveyor screw to a tank 7 feet deep and measured at once it weighs 31½ lbs.; in twenty-four hours it will reach 35 lbs., and increases in density till in six weeks without jarring it will weigh 38½ lbs."

Compressed air transport was largely developed by the Quigley Company. The powdered fuel is collected in large central storage bins, from which it falls through slide valves and pipe connexions into cylindrical blowing tanks (these in some installations stand on weighing scales; the pipe connexions from the bins must then be flexible so as to allow sufficient motion for the scales). The tanks may be as much as 6 feet in diameter and 18 feet high, and hold up to 4 tons. A 4-inch pipe leads from about a foot above the bottom of the tank vertically through the roof, just above which there is a control valve, past the system of furnaces to be supplied, and has a two-way valve and branch pipe to each furnace bin. When the tank has been filled with fuel, communication with the storage bin is shut off, and the tank is connected with a compressed air supply delivering air at a pressure about 30 lbs. per square inch. The operator has an arrangement by which he can control the valves to every furnace bin, and when desired to send coal to a particular bin he opens the appropriate valves, and delivers coal until the scale reading of the blowing tank shows that the appropriate amount has been sent. Above each furnace bin is a cyclone collector, which separates the powdered coal and the air; the coal falls into the bin, and the air escapes at the top

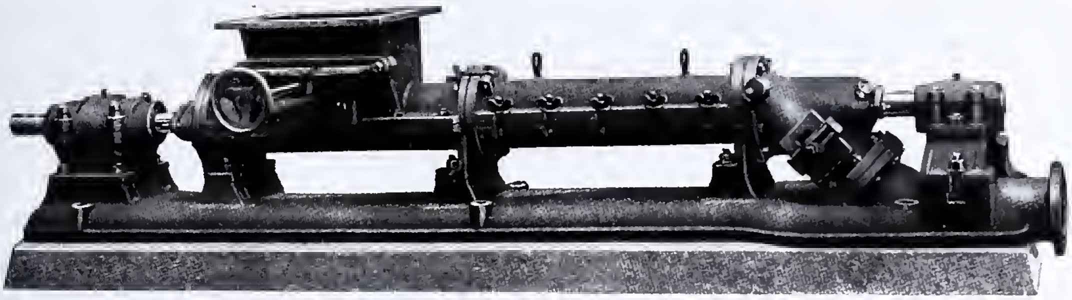

Fig. 23.—Fuller-Kinyon Pump

of the collector. The system is shown diagrammatically in Fig. 24, and a view of the storage bins and tanks in Fig. 25.

In this system the air mixes with the coal only to a limited extent, but drives the coal through the pipes almost in the condition in which it exists in the blowing tank. About 1 cubic foot of air at atmospheric

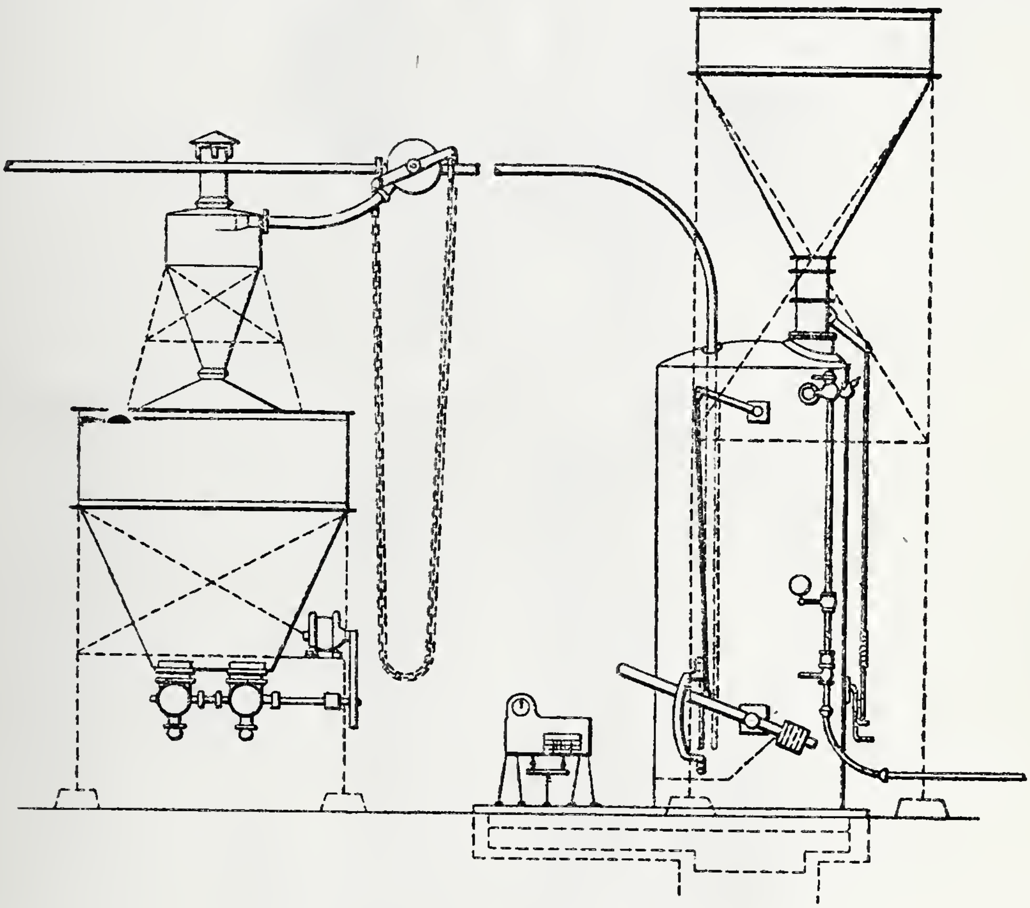

Fig. 24.—Quigley Transport System

pressure is used for the transport of 1·5 to 2 lbs. of coal. It is stated that 2800 lbs. of coal have been transported 600 feet through a 4-inch pipe in a minute with an average air pressure of 15 lbs. per square inch. The energy needed is estimated at about 7 h.p. hours per ton conveyed that distance. A compressed air tube runs by the side of the fuel pipe, into which it has connexions through valves at intervals, so that possible obstructions in the fuel pipe may be blown away by the compressed air. Evidently absolute tightness of the whole system and clean working of the shut-off

valves between storage bins and blowing tanks are of the first importance in this system.

The Fuller-Kinyon pump is a combination of mechanical and pneu-

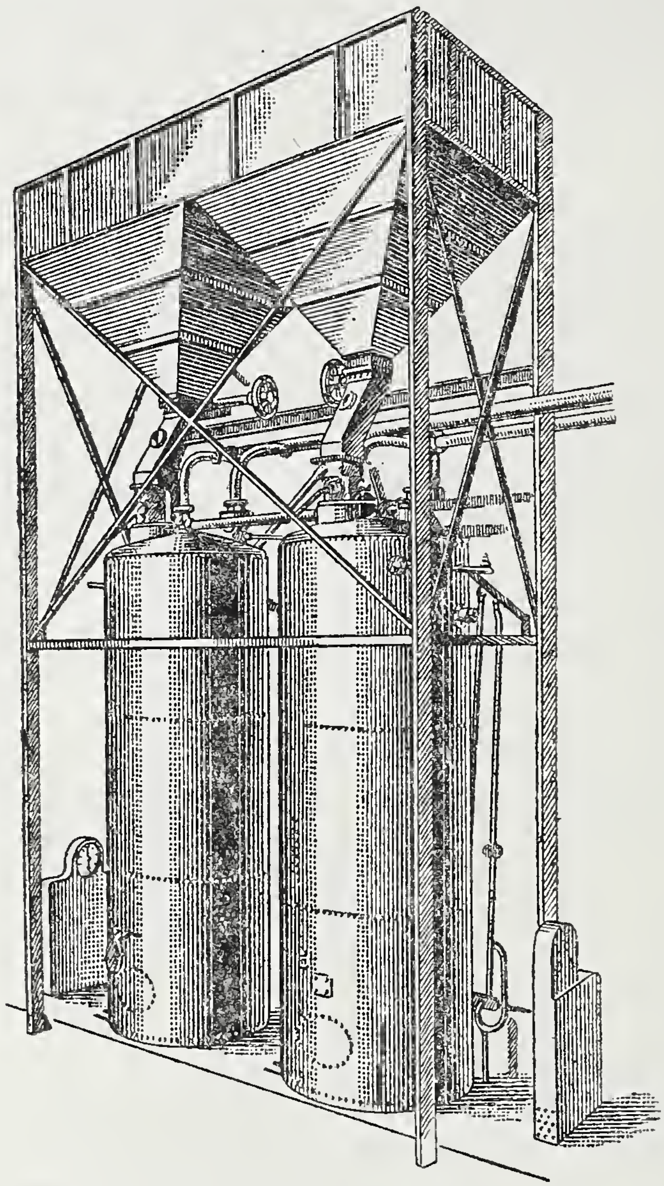

Fig. 25.—Quigley Storage Bins and Tanks

matic transport. The pump itself (Fig. 23) is a rapidly rotating helix, which receives the powdered coal from the storage bin, and drives it through the transport line. At the point where the pump barrel delivers to the transport line, a jet of compressed air enters the system. This

mixes with the powdered coal, and renders it more "fluid," so that it more readily traverses the pipe under the impelling force from the pump and the expansive action of the air. The general arrangement of the system is seen in Fig. 26, which shows the air compressor, receiver and piping, as well as the helical pump. On the transport line are indicated two branches, with valves, showing how from the one conveyor any number of separate sections or furnaces may be fed. The air pressure varies from 15 to 30 lbs. per square inch, according to the length of line and the lift, and the amount of air introduced is about 6 cubic feet (at atmospheric pressure) per ton of coal. With this small amount no cyclone separators are needed at the receiving bins (as seen in the figure), which simply have small vent stacks mounted upon them. A 6-inch pump will propel 9 tons of coal per hour a distance of 350 feet, or 4 tons per hour 1250 feet. The energy needed is from 1·3 to 1·8 h.p. hours per ton of coal, according to the distance or circumstances of travel.

The advantages claimed for this system are that, because of the simplicity of the pump, and because the conduits are of wrought-iron pipe, and thus need no heavy supports and permit of the use of bends, the cost of installation is very low; that the wearing parts are reduced to a minimum, and thus the maintenance is very small; that the consumption of energy per ton of material moved (including the energy for air compression as well as that for driving the pump) is less than that needed for any other method of transport; that the system is clean, as connexions to the wrought-iron pipe can be made absolutely tight; and that, the amount of air introduced being so small, the mixture in the transport line does not approach explosiveness, so that the system is absolutely safe. If desired, a weighing bin can be installed above the pump, and the amount of coal delivered to any part of the system measured by the amount fed from the weighing bin to the pump.

The Holbeck system is entirely different from those hitherto considered: in it the transport of the coal is effected entirely by the motive power of a high-pressure blower. The working of the system will be understood from the diagram in Fig. 27. The coal, delivered to the installation and passed through the drier and pulveriser, is drawn and

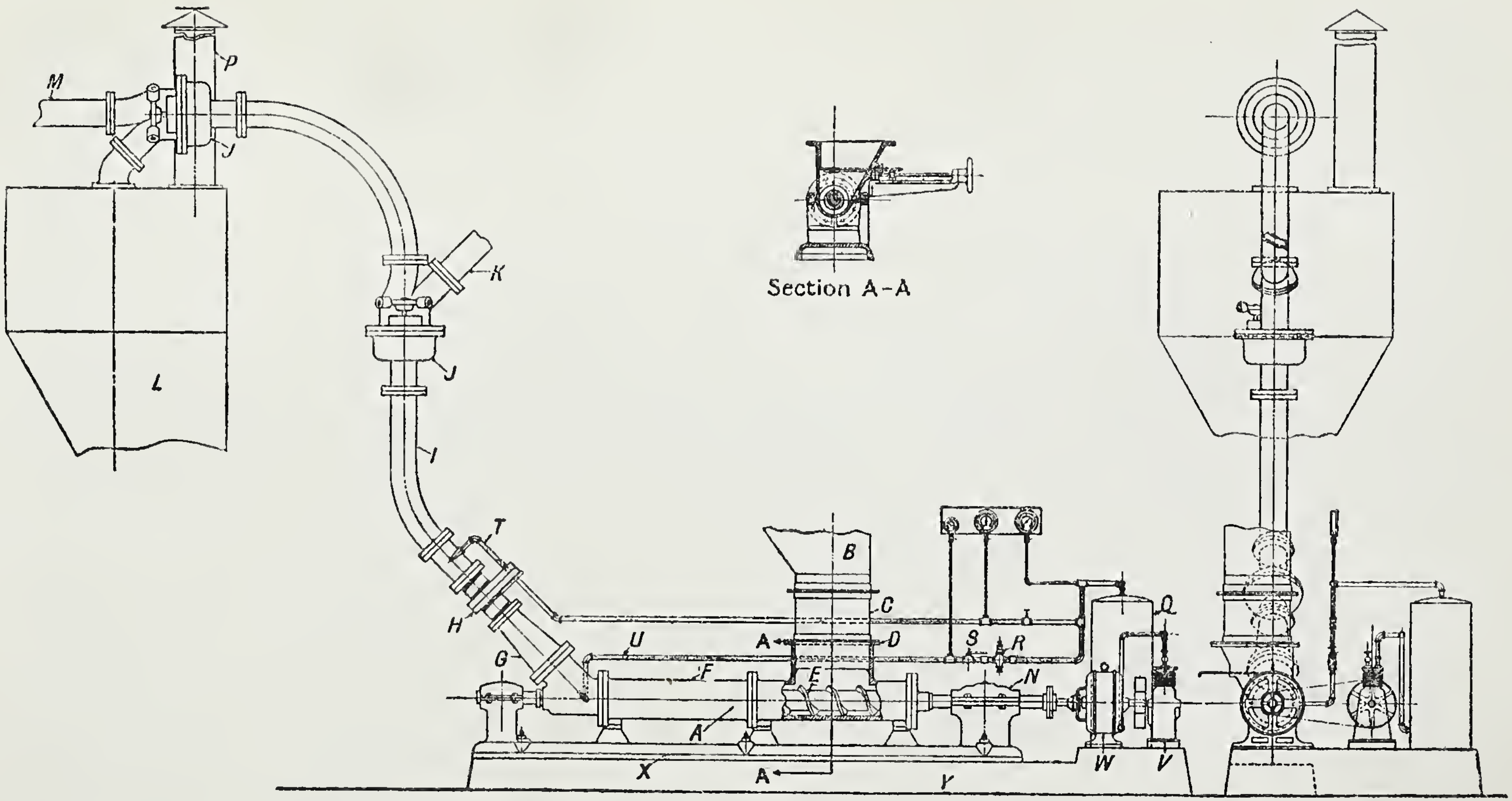

Fig. 26.—The Fuller-Kinyon Pulverised Material Conveyor System

A. Fuller-Kinyon 6″ Pulverised Material Pump.
B. Material Bin.
C. Supply Spout.
D. Pump Hopper.
E. Forcing Worm.
F. Pump Barrel.
G. Reducing Nozzle.
H. Single Diverting Valve.
I. Converter Conduit.
J. Two-way S.K. Valve.
K. Branch Conveyor.
L. Receiving Bin.
M. Continuation of Conveyor.
N. Main Bearing.
P. Vent Stack to Receiving Bin.
Q. Air Receiver.
R. Pressure-reducing Valve.
S. Air Valve.
T. Conduit clearing Air Line.
U. Aerating Line.
V. Air Compressor.
W. Electric Motor.
X. Pump Base.
Y. Foundation.

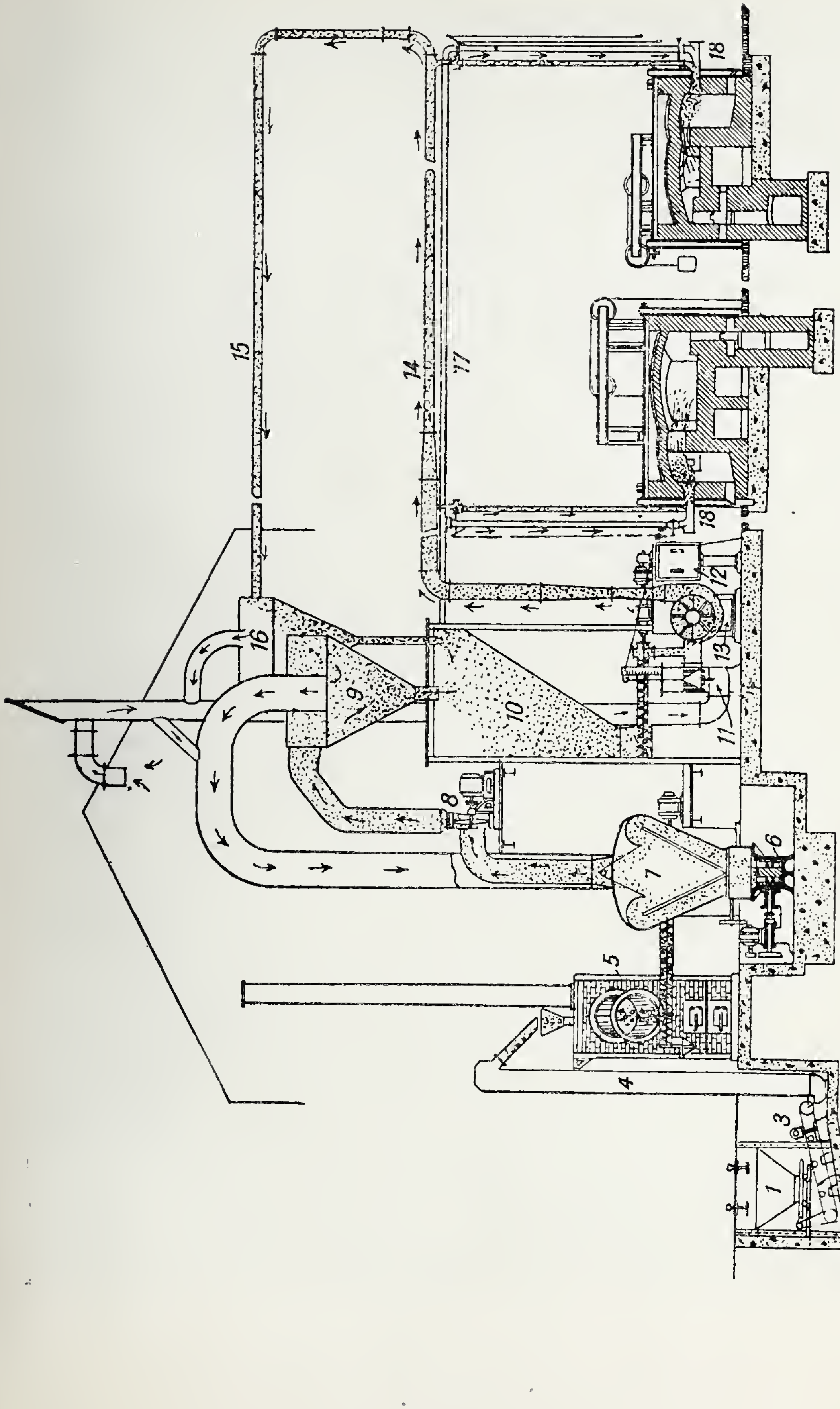

Fig. 27.—Holbeck System of Transport

1. Unloading Hopper.
2. Belt Conveyor.
3. Magnetic Separator.
4. Bucket Elevator.
5. Rotary Coal Drier.
6. Pulveriser.
7. Air Separator.
8. Exhauster.
9. Main Collector.
10. Powdered Coal Bin.
11. Air Indicator.
12. Automatic Regulator.
13. Distributing Blower.
14. Powdered Coal Main.
15. Return Pipe.
16. Return Collector.
17. Secondary Air Main.
18. Burner.

driven by the separating fan to the collector 9, whence it falls into the storage bin 10. The screw conveyor from the bottom of the bin carries it along and drops it into the entry duct of the distributing blower 13, through which it passes, along with the air which is drawn into the blower at the same time ; and the mixture of coal and air is blown through the powdered coal main 14, which extends past all the furnaces to be fed from the system, through the continuation of this main which becomes the return pipe 15, and into the return collector 16. Here the coal and air are separated, the coal falling again into the storage bin, and the air being carried from the top of the collector into the entry duct of the blower, so that any fine coal it may still contain remains in the system, and is not lost. Branch pipes, governed by valves, lead from the powdered coal main to the furnace burners, as shown at the two burners 18 in the diagram ; and as soon as any valve is opened, the mixture of coal and air is supplied to the corresponding burner. So far all is simple ; but it is clear that, unless there is some means of controlling the supply of coal and air to the main, variations in the load caused by variations in the number of burners at work or the rates of feed at the burners will cause variations in the pressure in the main, and irregularities in the working of the furnaces. There must always be sufficient coal in circulation to leave a surplus on occasions of maximum demand, and yet on occasions of small demand the pressure must not rise beyond that needed for efficient working of the burners which are at work. This control is effected automatically by the regulator 12 and the air indicator 11. When a valve is opened so as to admit air and coal to a burner, the pressure in the trunk line is momentarily reduced ; this opens a valve in the air indicator, and in opening it operates mechanism in the regulator, which increases the speed of the variable speed motor which drives the feeding mechanism from the storage bin. An increased supply of coal is thus afforded to the blower ; and as at the same time the air indicator has provided for the admission of more air, the deficiency caused by the demand of the furnace is exactly made up, and the quantity of coal in circulation, as well as the ratio of coal to air, is kept constant. When all the furnaces cease work the feed of coal is stopped, and in a very short

time the whole of the coal in the circulating system is restored to the bin and the system left empty.

The amount of air mixed with the coal in the main is nearly one half of the total quantity needed for combustion, or 50 or 60 cubic feet per lb. of coal; most of the remainder of the air needed is supplied as "secondary air" at the burners. The diagram shows the secondary air main 17, with its branches to the burners.

As the coal in the whole system, including that in the storage bin, is continuously in motion when the plant is at work, the likelihood of clogging or bridging, which may occur when the coal is at rest in the bin, is very much lessened. The continuous motion, however, also implies continuous abrasive action; and the wear, especially of the fan and casing, may be considerable, especially with hard or ashy coals. In this system some of the energy of the compressed air is utilised at the burners; in the Quigley and the Fuller-Kinyon systems it is all lost.

In extended installations a second blower has been installed in the main, to keep the coal and air circulating at the proper speed. The pressure at the main blower is about 20 inches of water column, and the energy required to maintain the system seems to be from 35 to 40 h.p. hours per ton of coal, though it must of course vary with the extent of the installation and with the ratio which the average load on the system bears to the full load.

The mixture of coal and air contains much less air than is requisite for complete combustion, and the speed of transport through the main, some 80 or 90 feet per second, is above the speed of flame transmission for the mixture, so that there is no fear of explosion whilst the system is at work. Tightness of the whole system, however, and especially of the valves to the burner branches, is very necessary; and valves to prevent back lash of air from the burners are desirable for safety's sake.

In unit installations the mixture leaving the mill for the burner may contain practically the whole of the air for combustion, and be explosive; but its speed through the delivery pipe till it reaches the burner is (because of the greater amount of air it has to carry) still greater than in the Holbeck

system, and the total volume of explosive mixture at any moment is so small that no danger further than the bursting of the delivery pipe is to be apprehended even though explosion should occur.

As with pulverisers, so with methods of transport; no system is universally superior, and the choice of a system depends on the relative weight to be attached to superiority in one direction or in another. In some instances only one method may be practicable; in others any may be chosen.

Bunkers at the furnaces are cumbrous, take up valuable space, and obstruct the view across the house; but each bunker is independent of all the others. Anything going wrong at a particular furnace affects that furnace alone, and a stoppage in the supply system does not mean stoppage of the work of any constituent furnace until the supply stored in the furnace bunker has been exhausted. With the Holbeck system the whole of the furnaces are dependent upon the continuous and regular working of the control supply.

For small installations the unit system alone is applicable; the cost of central station and transport plant would be prohibitive. For larger systems, screw conveyors seem adapted for the transport of large quantities through short distances, and either the Fuller-Kinyon pump or high-pressure air if the distances are great and the quantities large—both of these systems are very elastic. Medium distances suit the Holbeck system best. With an irregular load, the power needed for the Holbeck system is greater than that needed for the Quigley or the Fuller-Kinyon; and the uniformity of the Holbeck mixture may be a little difficult to secure at high loads—to have pipes capacious enough to be quite independent of the loads at the units would mean a higher expenditure of power. For scattered furnace- or boiler-houses, it would seem practicable to supply each house from a central mill by high-pressure air or the Fuller-Kinyon pump, and to distribute in each house by the Holbeck system.

BURNING

The design and construction of feeders and burners and the admission of combustion air to the furnace are of the greatest importance, and it is possible that much of the earlier grief in connexion with powdered coal burning may be attributed to lack of appreciation of this fact.

The feeder should be so designed as to give a positive uniform flow of coal, widely variable as to capacity, with this range immediately responsive to operating demands, and should be so substantially constructed as to make it free from interruptions to service. The burner should be of substantial structure so as not to warp and should have means for very close regulation of air.

In unit installations of the turbo-pulveriser or Bettington type the mixture of powdered fuel and air is supplied direct from the mill to the burner. In the Bettington boiler the whole of the air needed for combustion goes in through the mill, and the pipe from the mill to the burner is filled with an explosive mixture ; the flame is prevented from passing back by the speed of the current and the cooling of the burner nozzle (see Fig. 28). The burner is a plain circular pipe, a continuation of the pipe from the mill, but is surrounded by a jacket through which cold water circulates. (This particular boiler was designed to work alternatively with gas, and the outer annulus, with connecting flange to the right, is the gas entry.) In the turbo-pulveriser the burner is also a plain tube, though not jacketed. Although by regulation of the openings for admission of air the whole of the air needed for combustion can be introduced into the mixture before it leaves the mill, yet very often less air is so introduced, and secondary air is admitted to the furnace, either by induced draught or by fan pressure, around the burner nozzle. The pulveriser is usually erected close to the furnace, so that the fuel mixture has but a short length of pipe to traverse, and no settlement or segregation of coal-dust can occur.

In the Holbeck system the condition of things between the circulating main and the burner is the same as that between the pulveriser and the burner in the unit system ; the short lead from the main is filled, as

soon as the valve is opened, with the already formed mixture of fuel and air, which is delivered at once to the burner. Here, however, the proportion of air is much less than with the Bettington mill or turbo-pulveriser,

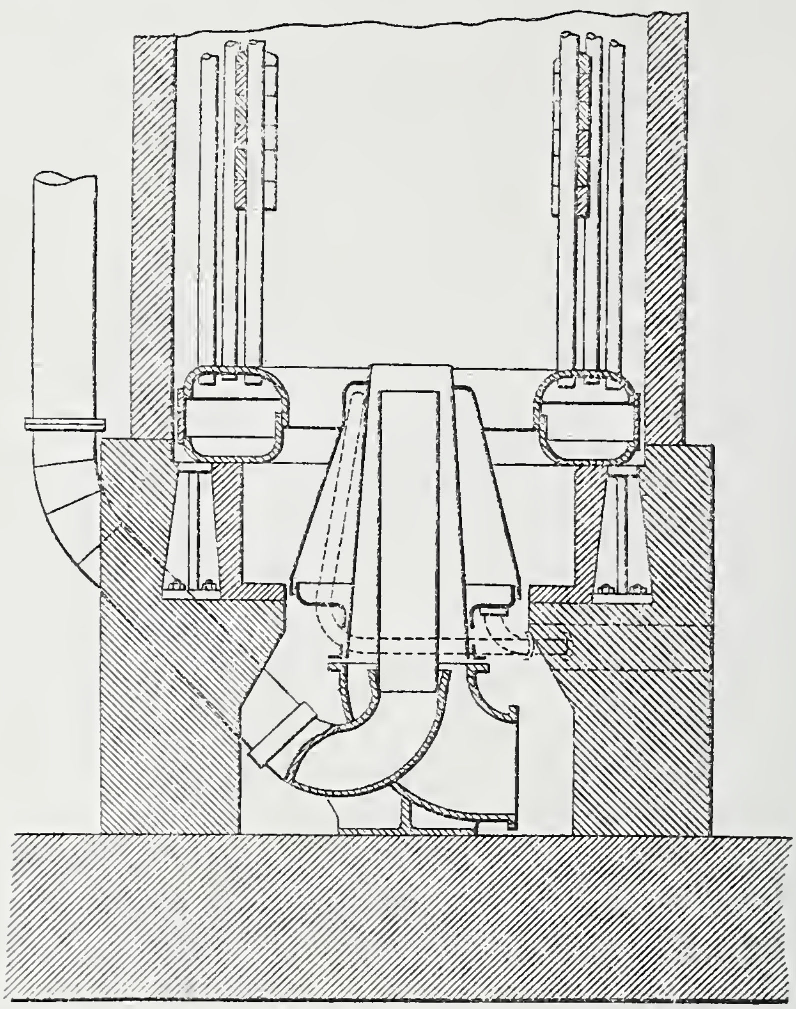

FIG. 28.—BURNER—BETTINGTON BOILER

and a considerable amount of "secondary air" has to be delivered from the air service.

The manner in which this is effected is shown in the diagram of the burner (Fig. 31). The mixture of coal and "primary" air enters by the side tube nearest to the burner mouth, and the "secondary" air by the wider tube behind it. The pressure in the secondary air circuit is always lower than that in the main circuit, to avoid the possibility of air being

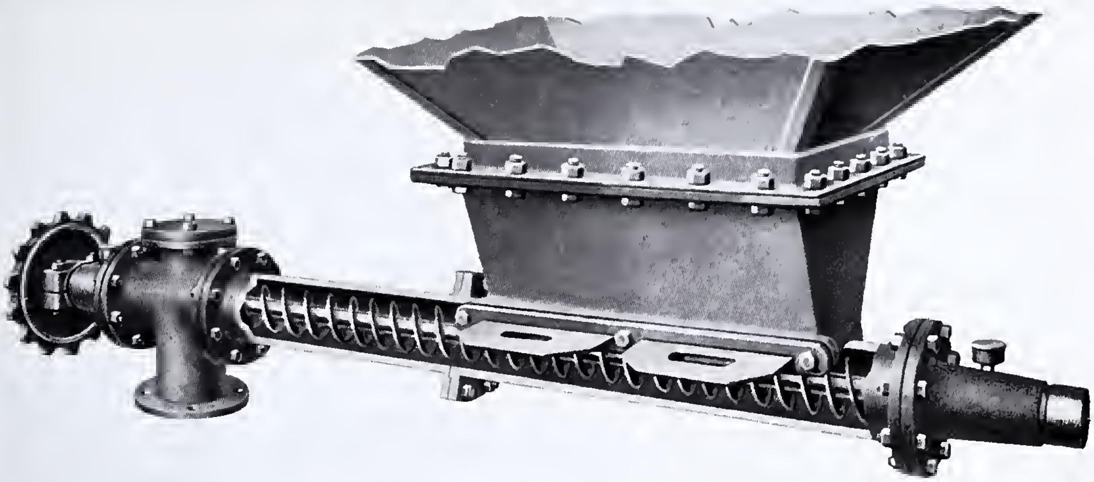

Fig. 29.—Fuller Feeder

Fig. 30.—Fuller Burner

driven back into the main circuit, and of an explosive mixture being thus formed. As with the turbo-pulveriser, so here: the coal and air mixture already contains nearly half the amount of air needed for combustion, and the capacity of the secondary air service allows of the whole of the remainder being fed into the burner; but it can be regulated so as to supply less than this, and the deficit can be made good by entry at the furnace in other ways, if this be found more efficient or otherwise desirable.

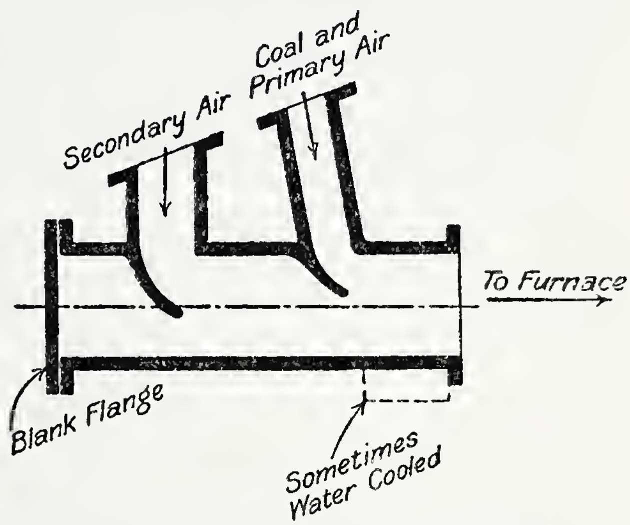

FIG. 31.—BURNER—HOLBECK SYSTEM

In those installations in which storage bins are mounted at the furnaces, arrangement has to be made for the regular, and regulable, supply of pulverised fuel from bin to burner, and for the introduction, and admixture with the coal, of the requisite amount of air. In the Bettington boiler, and in the turbo-pulveriser, regulation of the quantity of coal supplied to meet the varying demands of furnace or boiler is effected by altering the quantity of coal fed into the pulveriser. In the Holbeck system the variable speed motor actuating the feed from the main storage bin automatically effects the regulation, and the supply to each furnace is regulated by manipulation of the valve on the burner branch. In the other systems various forms of feeder, mostly variants of the screw conveyor, are made use of.

The Fuller feeder is shown in Fig. 29. Its hopper is fastened to the bottom of the storage bin, and the slide gates can open or shut off the supply of pulverised coal. The feeders are made with 2-inch to 6-inch screws, and have capacities, at 110 revolutions per minute, of from 400 to 6500 lbs. per hour. The capacity of any one feeder is roughly proportional to the speed of revolution, up to 200 revolutions per minute, and motors of from $\frac{1}{2}$ to 1 h.p. are sufficient to drive the feeders. From the end of

the feeder the coal drops through an attached vertical pipe to the burner. The Fuller burner is shown in Fig. 30, and in section in the diagram, Fig. 32. The coal drops down the vertical tube, and is distributed by the inclined deflector, into the inner tube. Air under pressure enters at the back of this tube, its amount being regulable by the blast gate, and mixes with the coal. The current of air and coal issuing from the inner tube draws secondary air into the outer tube, the amount of which can be

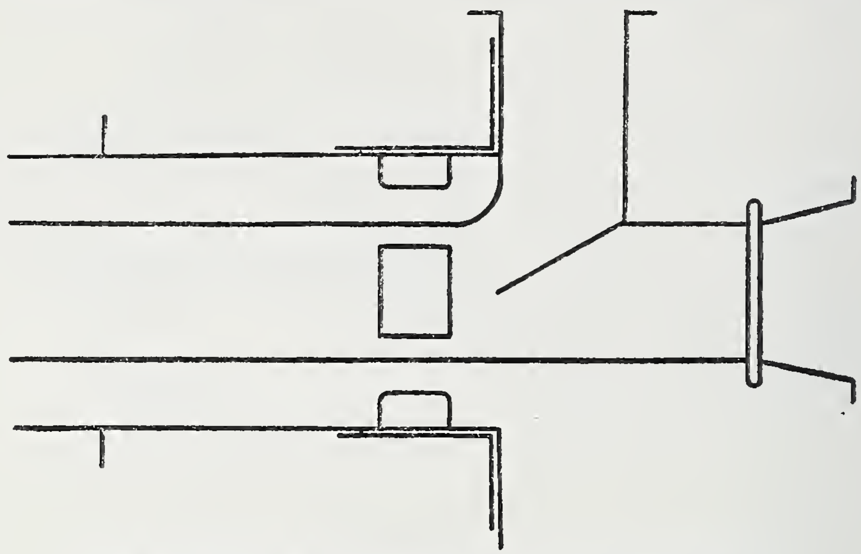

Fig. 32.—Fuller Burner—Diagrammatic Section

controlled by partially closing the openings by means of the adjustable shield. The burners are made with various forms of orifice, and with either vertical or horizontal introduction into the furnace, to suit the particular furnace concerned.

The Rayco burner of Messrs Raymond Brothers, shown in its horizontal form in Fig. 33, is also a double tube burner; but in this the coal is introduced into the outer annulus, not the central tube. The burner divides the air supply into two parts, one passing through the outer annulus and carrying the coal with it into the furnace as a hollow cylinder, the other passing through the inner tube. This air, emerging from the burner mouth, expands, disperses the coal particles, and effectually brings coal and air into intimate contact so as to secure complete combustion. Though the coal and air enter the furnace at low speed, there is no danger

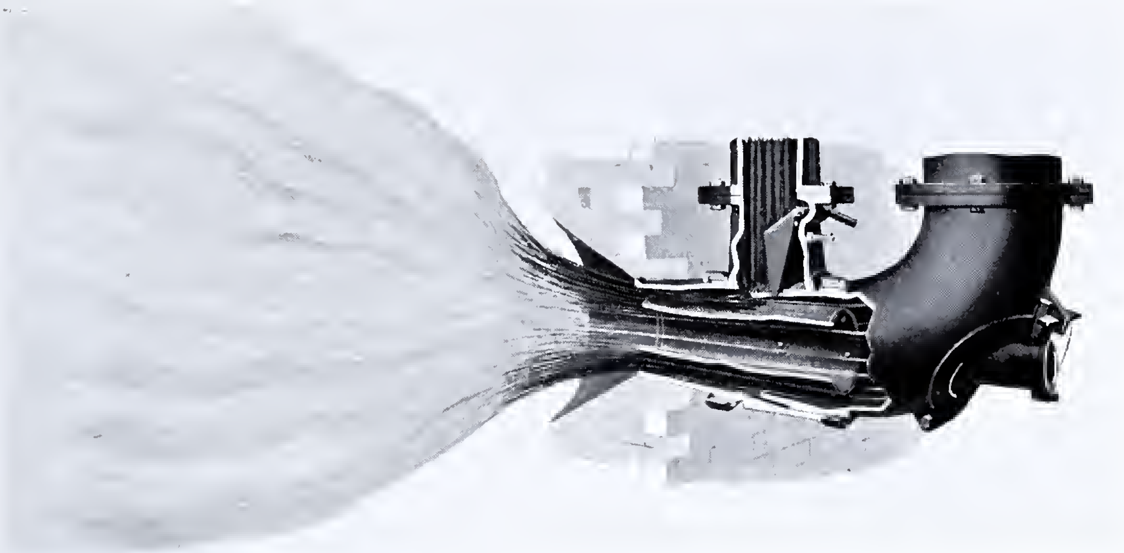

Fig. 33.—Lopulco Burner

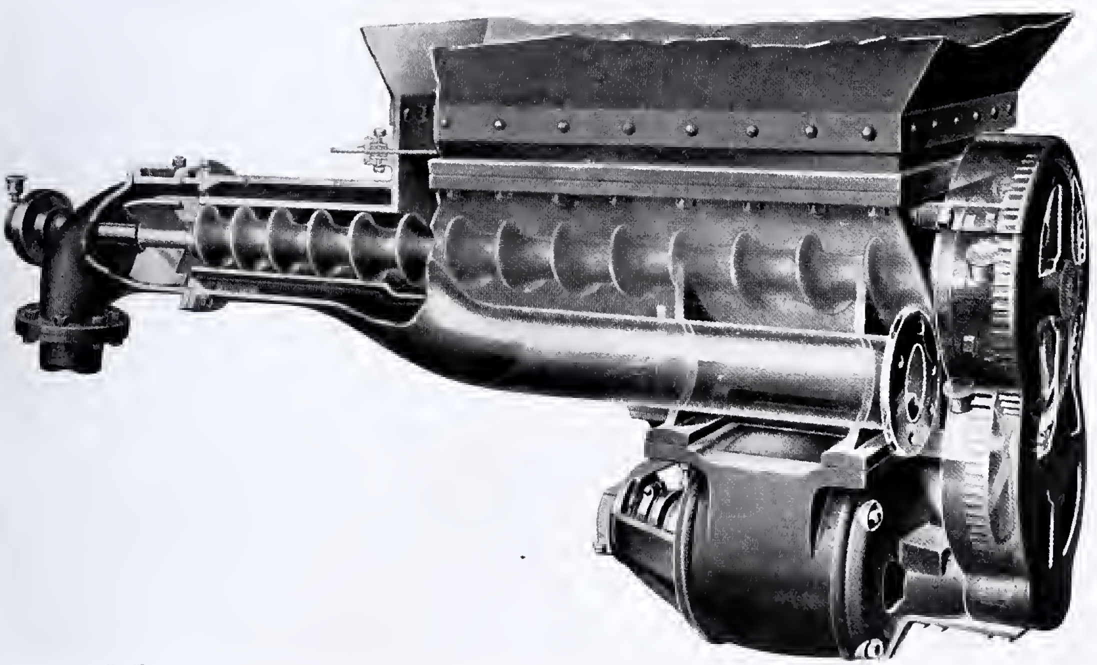

Fig. 34.—Lopulco Feeder

of firing back, because of the small amount of air that is actually mixed with the coal in the burner tube itself.

In the Lopulco feeder of the Combustion Engineering Co., whose rights in Great Britain have been acquired by the Underfeed Stoker Co., air is introduced into the coal on its way to the burner. From the hopper attached to the bottom of the bin (Fig. 34) the coal falls into the conveyor, the screw of which is actuated by a variable speed motor. Towards its exit end the housing of the screw is surrounded by an annulus, into which air is blown from the pipe seen below the screw in the figure. The coal and air are churned together by the paddles on the end of the screw shaft, and pass into the vertical pipe leading to the burner.

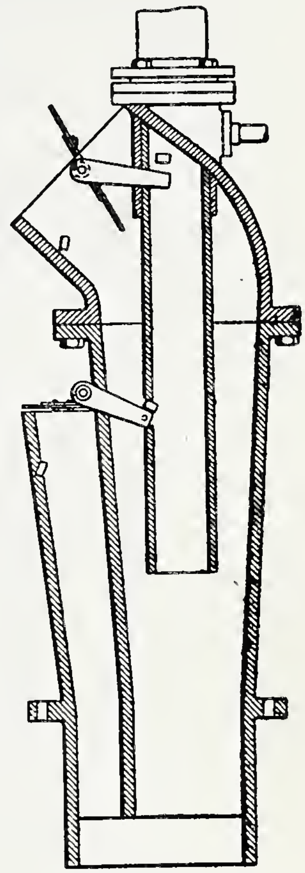

Fig. 35
Lopulco Burner

In the Lopulco burner, seen in Fig. 35, the mixture of coal and air is blown in through the central pipe, and secondary air is drawn in through both of the openings shown. The central tube terminates some distance from the outlet of the burner, so that a certain amount of expansion and mixture with the secondary air occurs before the nozzle is reached. Combustion under these circumstances is very rapid. The original mixture contains about 10 per cent. of the air needed for combustion, the rest entering through the air ports or through auxiliary openings in the furnace front.

The burner installed in the Milwaukee power stations is seen in Fig. 36 (Kreisinger and Blizard, *Proc. Eng. Soc. of W. Pennsylvania*, 1922, xxxviii. 177). About 15 per cent. of the air needed for combustion is supplied with the coal under a pressure of 7 to 12 inches of water; 15 to 20 per cent. is supplied by induced draught through the burner around the nozzle, and 65 to 70 per cent. through the hollow walls of the furnace.

For efficiency the burners must be fed regularly and must function

properly. In most of the feeders of the screw conveyor type the rate of feed is regulated by the speed of rotation of the screw, which is usually driven by a variable speed motor ; in the Quigley conveyor, however, the rate is controlled by hand regulation of the size of the opening through which the coal is delivered from the bin to the conveyor. The continuity

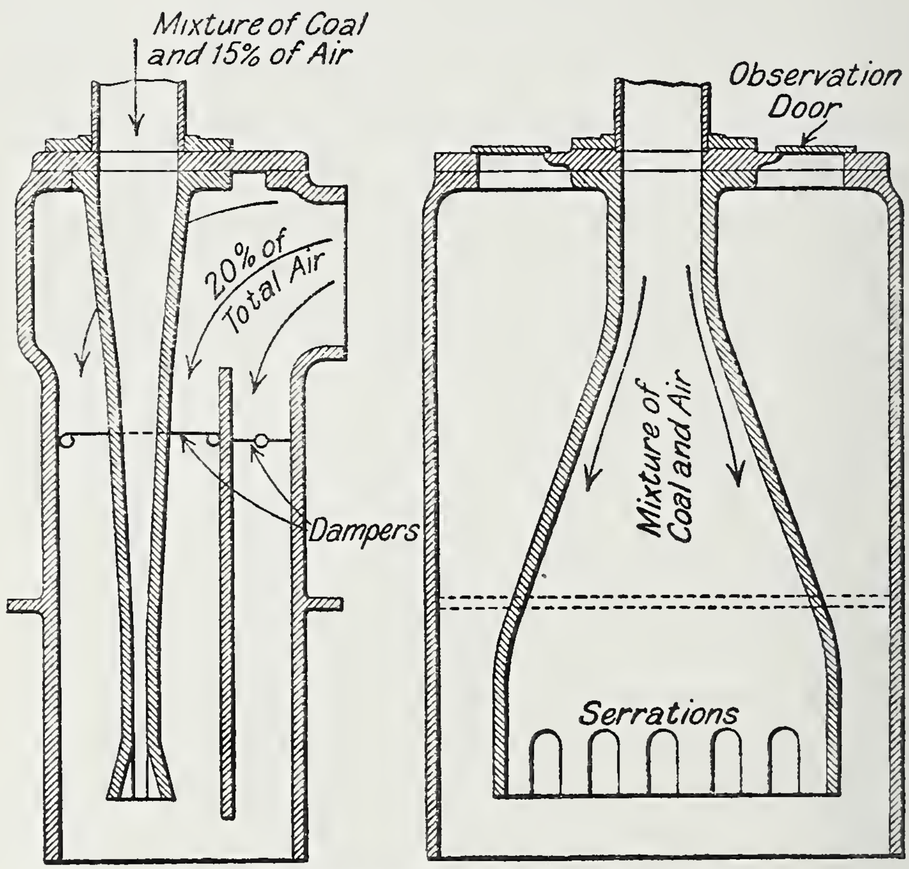

Fig. 36.—Burner—Lakeside Power Station

and regularity of the feed depend upon the continuity of the fall from the bin, and everything must be done to avoid clogging or bridging. The dryness of the powdered coal in the bins is therefore a very important consideration. Not only must the coal be dry when delivered into the bin, but dryness of the atmosphere must also be secured as far as possible ; the temperature of the bin should be above the dew-point, so that no condensation of moisture on the coal from the air in the bin can occur. A temporary stoppage of the supply to the burner involves not only the

extinction of the flame, but the possibility of explosion. In one arrangement the conveyor from the bin drops the coal into a second parallel conveyor travelling in the opposite direction, just a few inches below. The upper conveyor brings more coal than the second can take away, and the surplus is returned by a third conveyor to the bunker outflow. In this way the second conveyor is supplied always with a sufficiency of coal, whatever may be the level in the bin; but experience has shown that such an elaborate arrangement is not necessary. There is another difficulty connected with conveyor transport to the burners. "Powdered coal will flush, and when once started will run like water. Screw-feeding devices should therefore be made very long, and of a reasonably fine pitch, in order to set up enough friction and baffling action to prevent the coal from flushing through the feeding mechanism and causing irregular feed."

The conditions of combustion of powdered coal are not quite the same as those of the combustion of gas. In the first place, finely as the coal is pulverised, the particles are still far above molecular size, and hence the mixture of coal and air is not nearly so intimate as that of gas and air, and the combustion cannot therefore be quite so rapid. Again, gaseous diffusion ensures that a mixture of gas and air, once made, will remain uniform indefinitely, whilst the coal continually tends to settle out from admixture with the air. Further, the combustion of each particle of powdered coal, though much more rapid than that of a piece of sensible size on a grate, yet follows the same order—that is to say, the coal is first carbonised, with production of gaseous products and of a non-volatile carbonaceous residue, and the gases burn with greater facility than the carbon. The burner has therefore to be designed so as to ensure that the coal particles are brought into contact with the air intimately enough, and long enough, to permit these successive actions to take place completely. Many of the early troubles with powdered coal firing arose from the delivery of the mixture from the burner at too high a speed; and modern practice has aimed at reducing this speed as far as is consistent with keeping the coal suspended till it is burnt: partly through the construction of the burner, partly by reducing the pressure and hence the

speed of the air current. Apart from considerations of complete combustion, high speed tends to carry forward the zone of highest temperature and to strain the resistance of the refractory lining of the furnace. There is also the risk of the projection of flame from sight holes or other openings. The pressure of the air may be anything from 1 to 10 inches of water column, according to the construction of the burner, and according as it is introduced as primary air carrying the coal with it, or as secondary air. A study of the forms of burners described shows that efficient combustion can be attained under very varied conditions of mixture of coal and air ; which of these forms is to be preferred in any particular case can only be decided by consideration of the circumstances of the furnace and the objects to be attained. A boiler and a melting furnace need different treatment, and the burner best adapted to one is not necessarily best adapted to the other.

Burners usually will not work so efficiently at much less than their designed load ; hence where the load is variable a number of small burners will probably do more satisfactory work than one large one. Most of the forms of burner are made in many sizes, capable of burning from 25 to 3000 lbs. of coal per hour.

FUELS SUITABLE FOR POWDERED FUEL FIRING

One of the claims made for powdered fuel firing is that inferior fuels of various kinds, low in calorific value and high in ash, can be economically used. Naturally, such fuels need more preparation and cost more in use than richer fuels do, and hence can only be used industrially if the price at which they can be obtained is sufficiently low to compensate for this. If we are comparing a coal containing 10 per cent. of ash with one containing 40, we have to take into account, not only the fact that to obtain an equal amount of combustible we must pulverise 90 tons of the poorer fuel for every 60 tons of the richer, but also the circumstance that in all probability the poorer coal will be harder than the richer one, so that the cost of grinding, both in direct power needed and in wear of the pulveriser, will be much more considerable for the poorer coal. There will also be the

transport, through the drier as small coal, and through the distributing system as powder, of 90 tons of poor fuel against 60 tons of rich; and, again, both because of the greater quantity, and also because of the greater density and probable greater hardness of the particles of the poor fuel, the wear on fans and pipes will be greater with the poor fuel than with the rich. Probably both can be burnt with an equal approach to completeness—here we have the great advantage of powdered fuel combustion coming in—but when they are burnt the 90 tons of poor fuel will leave 36 tons of ash to be removed, whilst the 60 tons of rich fuel will leave only 6 tons—one-sixth of the amount.

There are, however, many fuels now obtainable at such prices that, after all these extra sources of working cost are taken into consideration, their use can effect very considerable saving; and it is because it is practicable to use them in the powdered form, while they could not be used at all over grates, that the extension of powdered fuel firing offers hope of a real economy in the utilisation of our coal resources.

The fuels best adapted for burning in the powdered form are bituminous coals, with a moderately high content of volatile matters. These ignite at a lower temperature than coals of an anthracitic character, which are correspondingly difficult to burn. Anthracites, especially the small and otherwise waste portions known as "culm," have been successfully burnt, however, not only in mixture with bituminous coal, but alone. The difficulty here is almost entirely one of ignition temperature. It may be practically impossible to burn an anthracitic dust starting with the furnace cold, or warmed only by an initial fire made in it for the purpose simply of setting alight the powdered fuel; but if powdered bituminous coal be used to start the work, and be supplied until the combustion chamber has reached, or nearly reached, its normal maximum temperature, and the change be then made to anthracite, the anthracite will burn freely and completely.

Coke presents itself as a cheap fuel for use in powdered form, for there are large quantities of small and breeze available for which it is now very difficult to find a use. There is not likely to be much difficulty in the way of burning powdered coke, for its ignition is not more difficult

than that of anthracite; but the extreme hardness of oven-coke, and the consequent very great wear on the mills and the transport system, constitute a much more formidable obstacle in its way—the more so because, with a substance containing little else than solid carbon, like coke or anthracite, fine grinding is more important for its complete combustion than it is with a bituminous coal.

The semi-coke yielded by low-temperature distillation of coal is not nearly so hard as the product from high-temperature coke ovens, and to that extent would seem to be better adapted for use in the powdered form than coke. Messrs Edgar Allen & Co. have used "coalite" in the powdered form in a unit installation feeding a reheating furnace without finding any indication of unusual wear in the pulverisers. A report from them says:

"'Coalite' has proved to be an excellent fuel for use in our Turbo-Pulveriser. The consumption per ton of steel heated is about the same as with small slack coals which we use, about $4\frac{1}{4}$ cwts. The comparatively low ash in the coalite which we used (about 7 per cent.) reduces the work of cleaning the flues, and the low moisture (about 2 per cent.) fits it for readily powdering in the machine. Our usual forging temperature is 1100° C. to 1200° C.; but as an experiment we have raised the temperature of the furnace, when using coalite, to 1400° C."

The use of similar products in this way might give a considerable stimulus to the treatment of poor, high-ash coals by low-temperature carbonisation. The economic difficulty with such coals has been that the yields of oils and gas, whilst perhaps satisfactory in themselves, could not be remunerative unless an outlet could be found for the semi-coke. The only promising outlet for this seemed to be gasification in producers; but the very high ash content made this in many cases impossible. The use of such ashy semi-cokes as powdered fuel does point the way to a practicable solution of this problem.

Closely related to this is the possibility of using in powdered form some of the products of the Trent process. Mr W. E. Trent found that by agitating together powdered coal, water and oils the coal and the oil became associated in a plastic mass called by Mr Trent an amalgam, whilst

a considerable proportion of the mineral matter of the coal was separated and went away with the water. A high recovery of the total combustible matter in the coal is attained by the process, with very considerable reduction of ash. The further stage of the process consists in the destructive distillation of the amalgam, when the greater part or the whole of the original oil is recovered, together with liquid and gaseous products of the carbonisation of the coal, and a carbonaceous residue remains, which with many coals is pulverulent, and in any case is not so hard as coke. This residue would appear to be very suitable for further pulverisation and use as fuel in the powdered state.

Lignites lend themselves very well to combustion in the powdered form. They are easy to grind and they burn easily and completely. Their tendency to fall to powder, which renders them very unsuitable for grate burning, is no disadvantage when they are to be used in powdered form. Their disadvantage is the large amount of water which they contain, which makes drying compulsory and a little more costly than with ordinary coals. Against this is to be set the fact that the output of a mill is much greater with lignite than with coal, and that the power needed is less. In a recent test of Australian lignite, made by the Powdered Fuel Plant Co., an efficiency of boiler and superheater of nearly 81 per cent. was reached. This lignite contained, in the condition in which it was fired, 18 per cent. of ash, and had been dried so that it contained 9·7 per cent. of water, instead of about 45 per cent. in the original lignite.

The following account of a boiler using Australian lignite (" Morwell Brown Coal ") appeared in *The Times Trade Supplement*, 17th December 1921 :—

" The apparatus is fitted to a return tube boiler of the Cornish type. Galvanised-iron storage tank for the powdered lignite, to the bottom of which is attached a motor-driven feeding appliance, controlled by hand or by the pressure of steam in the boiler.

" Air supply furnished by a Root's blower at 1 lb. pressure, and is delivered into a stabilising tank, excess leaving by an exit. The air is forced into a mixing chamber below the pounded coal bunker, where it

mixes with the coal as discharged, and the mixture is carried in a 4-inch pipe.

"The burner, placed in front of the boiler setting, in the centre of the place formerly occupied by the fire-doors. The burner is so constructed that by turning a wheel control the flame can be increased or diminished so as to fill the combustion chamber without impinging on the chamber walls.

"About half of the air needed enters with the coal; the rest is induced. The temperature in the fire-box is about 1150° C., and that of the waste gases about 225° C.

"About 2 per cent. of the power generated is needed to work the apparatus. Of the ash, about 75 per cent. goes to the chimney, and of the remainder most lodges at the back of the combustion chamber, and is removed by a steam jet ash conveyor.

"The efficiency of the boiler, using Newcastle coal and hand stoking, is given as 55 per cent., with mechanical stoking, 70 per cent; using brown coal, 30 per cent. for hand and 35 per cent. for mechanical stoking; using pulverised brown coal, 75 per cent. The cost of Newcastle coal is 45s. per ton, of pulverised brown coal, 30s. per ton. One shilling expended in coal gives the following numbers of B.Th.U.:—

Newcastle coal,	hand stoked	325,000
,, ,,	mechanically stoked	470,000
Brown ,,	hand stoked	395,000
,, ,,	mechanically stoked	461,000
,, ,,	pulverised	560,000"

Peat has the same disadvantage as lignite, to an aggravated extent; but when it has been dried it is quite practicable to use it in the powdered form. Dried peat, containing about 14 per cent. of water, has been used as powdered fuel on locomotives in Sweden, and has given higher efficiencies than hand fired coal.

In making comparisons or calculations from published data as to the practicability and economy of using poor or high-ash coals, it must not be lost sight of that the ordinary coals of one country differ from those of

another, and that a coal considered suitable for a particular purpose in America or Germany might not be looked on as suitable for the same purpose in England, and vice versa.

In general it may be said that powdered fuel firing is more elastic in regard to the character of the fuel used than grate firing ; that a greater variety of fuels can be used with equal, or nearly equal, efficiency in a particular plant working with powdered fuel than in a particular plant working with grate firing. Moreover, if by alteration or modification of the burner work with any particular fuel can be rendered more efficient, such alterations or modifications are easily and cheaply made.

ASH DISPOSAL

The problem of dealing with the ash from powdered fuel installations is quite different from that which presents itself under the conditions of ordinary grate firing.

There practically the whole of the ash remains on the grate till it falls through into the space below, and the amount which is carried away into the furnace by the draught is negligibly small. The ash is, so to speak, simply uncovered as the surrounding coal burns away, and to a great extent remains as clinker, needing only to be raked out and carried away. But with powdered fuel the coal, and thus the ash, is introduced right into the combustion chamber. The ash is set free in the form of minute particles in the midst of the fierce heat of the flame, so that probably every particle is melted separately, and of these particles some are carried away in the current of gases, some coalesce with their neighbours and fall out to the bottom of the chamber. According to the construction of the combustion chamber and the nature of the ash, the deposit on the bottom of the chamber may be a loose and light powder, or a more or less completely melted and more or less viscous slag. Of that which is carried on with the gases some may be deposited in the flues, some be carried right through and into the open air at the top of the stack.

The method of removal of the ash depends obviously both upon the nature of the ash and upon the amount which the coal contains. There

are very wide differences among the statements published concerning the disposal of the ash, and the greater or smaller extent to which it affects the neighbourhood of the installation. In one case 60 to 70 per cent. of the whole is said to be deposited in the combustion chamber, and only 1 or 2 per cent. to go up the chimney ; in another, 30 to 50 per cent. is said to go up the chimney. Where a large proportion does go up the chimney, one account says that it deposits on everything in the vicinity, and constitutes an almost unbearable nuisance, whilst another says that it must be carried for great distances and dispersed over an enormous area, for no trace of it can be found in the district immediately surrounding the installation. The author's personal experience certainly supports the latter view, and the bulk of recorded experience also confirms it.

In metallurgical furnaces there is to be considered the possibility of the deposition of ash upon the objects to be heated or the products of the reaction ; these must not be capable of combining with or being spoilt by the ashes.

Elbows and angles are to be avoided wherever there is passage of flue gases containing ash. The use of regenerators and recuperators with powdered fuel is difficult, because of the choking up caused by the deposition of ash.

In early powdered fuel installations, cement furnaces were perhaps copied too closely. In these the great length ensures complete combustion, whatever be the amount of volatile matters in the coal, the speed of the gases, or the pressure ; and the ashes all go harmlessly into the clinker. But these conditions do not exist in other furnaces, and especially in boilers, where the combustion chamber is immediately followed by tubes or flues, where ash can accumulate and choke or block them. The difficulties are lessened by reducing the entrance speed of the fuel and gas, whether by lower pressure, by widening of the burner mouth, or by altering the direction of the burner ; or by expansion of the chamber as a whole, or by the addition of a fore chamber. Either of these plans tends to prevent the ash from being carried forward, and gives it a better opportunity for being deposited in the combustion chamber itself.

The disposal of ash is comparatively easy, if it be, on the one hand,

loose and powdery, or on the other hand, so liquid at the temperature of the floor of the combustion chamber that it will readily flow. Accordingly it is desirable, if possible, to choose a coal the ash of which, whatever its quantity, has either a very high or a very low melting-point. Difficulty arises when the melting-point of the ash is such that the original fine particles of ash are so soft at the temperature of the chamber floor or walls that they can clot or agglutinate, and form sticky masses which are neither liquid nor solid, will neither flow nor permit of being raked or shovelled.

The details of the furnace arrangement will depend on whether the ash is to be removed in the solid or the liquid form. If in the solid form everything possible will have to be done to keep the ash as nearly pulverulent as possible: to prevent it from agglomerating; and this will obviously be effected by lowering its temperature as rapidly as possible to below its melting or softening point. The individual particles of ash, as the coal burns away from them, and as they are exposed to the full heat of the flame, are no doubt always melted; but they rapidly radiate their heat, and should reach a zone of temperature at which they are solid before they are able to coalesce and blend into a mass. The introduction of secondary air over the walls and floor of the chamber is one means of helping to secure this; another means is to fit a screen of tubes through which some of the feed water circulates near the chamber floor. Both of these plans have been adopted in the power station at Milwaukee, which will be described later.

The difficulties of the earlier installations are indicated by Gadd (*J. Franklin Institute*, 1916, clxxxii. 329), who says: "One of the disturbing factors in the use of powdered coal is that of the large accumulations of ash deposited within the furnace, only a small proportion escaping through the stack. When using even a good grade of coal, ash will accumulate rapidly, and therefore fuel of low ash-content is always most to be desired."

When the ash is removed from the furnace in a molten condition, or indeed whenever it is removed at a high temperature, it must not be forgotten that it carries with it a certain amount of heat. If we suppose a

coal containing 15 per cent. of ash, and take the specific heat of the ash to be 0·25, and the temperature at which it leaves the furnace to be 1300° F. above the atmospheric temperature, then the ash from every pound of coal will carry with it $0{\cdot}15 \times 0{\cdot}25 \times 1300 = 48{\cdot}75$, or say 50 B.Th.U.—a small amount relatively to the total calorific value, 12,000 to 14,000 of the fuel, but a considerable absolute amount in a large installation. In so far as this ash is not withdrawn from the bottom of the furnace by the ash-door, but is carried on in the form of fine dust into the flue gases, it increases the amount of heat per cubic foot which those gases carry away, and if this heat be utilised in any way, the heat contained in the suspended ash is at the same time correspondingly utilised.

At the Oneida Street plant the arrangements for dealing with the ash are thus described by Savage :

"Probably the greatest grief in the earlier attempts to burn powdered coal was trouble from slagging, and those who are still sceptical as to the present-day state of the art are much given to laying undue stress upon this fact. Proper furnace design and correct air admission have practically eliminated this trouble, except with coals having a low fusing-point ash, but even with such coals the trouble is confined to extremely high ratings when coal in excess of 2 lbs. per cubic foot per hour is burned. This slag at extremely high ratings does not present any more serious problem than does the same condition of clinkering or slagging which occurs in stokers at extremely high ratings, and in powdered coal burning it does not interfere with the continuity of operation to the same extent that it does in stokers. At lower ratings, say up to 150 or 200 per cent., with coals having ash with a high fusing temperature, no slagging occurs, and the ash is in such shape that it is not necessary to remove the accumulation for several days, and this removal under these conditions simply necessitates raking the furnace out very much in the manner of cleaning the ash pits in any stoker practice. Under no conditions will there be any slagging of the tubes.

"With ratings of 200 to 300 per cent, carrying CO_2 around 15 per cent. and due to the low excess air necessary to maintain such conditions, there would be a high temperature maintained in the furnace. When using

coals with a low fusing-point ash under this condition there would be considerable slagging of the ash as it accumulated at the bottom of the furnace, which would make this removal difficult. As many of the coals throughout the country have a low fusing-point ash, much thought has been given to making operation with these coals at high ratings as simple and efficient as when using better coals. To this end a water screen connected in to the boiler circulation has been developed and applied to boiler No. 8 at Milwaukee. This water screen performs two functions. First, it acts as a cooling screen so that the ash falling through it to the bottom of the furnace is cooled and the zone below the screen is maintained at a temperature below the fusing-point. Second, it acts as a most efficient evaporating medium and produces one horse-power for approximately one square foot of heating surface. Results obtained with the screen so far have been most satisfactory. Operating at 200 per cent., CO_2 was easily maintained at 15 per cent. and there was no more than 50° difference between the temperature of the flue gases and the temperature of the saturated steam."

Kreisinger and Blizard (*Proc. Eng. Soc. W. Pennsylvania*, 1922, xxxviii. 169) describe as follows the means taken in the new Lakeside plant at Milwaukee for dealing with the ash :—" The ash of most clean coal fuses and runs like molten iron at a temperature of 2300° to 2400° F. When the temperature of the furnace lining exceeds that of the ash, the slag penetrates into the brick and washes it away ; but if the temperature of the furnace lining be kept below that of the molten ash, the slag on falling on the surface of the furnace lining is cooled to the temperature of the lining and becomes very viscous paste. In this state it does not penetrate the brick and wash it away, but forms a soft protective coating. To prevent erosion of brickwork by slag, therefore, the lining must be kept below the temperature of molten ash. If the ash is to be removed easily from the furnace, the falling particles of the molten ash must be cooled and solidified before they reach the bottom of the furnace, and the bottom itself must be kept below the temperature at which the ash is sticky. Then the ash deposited is in granular form and can be removed easily.

"The furnace of the Lakeside plant at Milwaukee has a water screen connected to the boiler, and hollow walls which supply 65 per cent. of the air used in combustion. The furnace lining is 9 inches thick and is separated from the outside walls by air spaces 9 inches wide. The air enters through openings in the rear wall of the furnace, passes through air channels in the two side walls, and enters the furnace through air openings in the front wall. The air takes heat out of the furnace lining, where it is not wanted, and puts it into the combustion space, where it is wanted. In passing through the air is heated to about 450° F., and thus keeps the temperature of the furnace lining below that of the running slag, and prevents the erosion of the brick. It also reduces the radiation losses, as the outside surface of the furnace walls is at a temperature not more than 15° above that of the surrounding air.

"The water screen is placed about 3 feet above the bottom of the furnace. It consists of two rows of 4-inch tubes rolled into a common header in front. In the rear each row of tubes connects to a separate header placed at such an elevation that, while both rows are inclined relatively to each other, each row is inclined to the horizontal at the same angle as the tubes in the boiler are inclined. This slope gives the water in the tubes a circulation. The effect of the screen is threefold: (*a*) it absorbs from the flames by radiation an amount of heat equivalent to about 400 boiler h.p., and thus makes the furnace temperature considerably lower, and helps to keep the temperature of the furnace lining below that of the running slag; (*b*) it cools and freezes the particles of the molten ash, as they fall through it, so that they are deposited in granular form; (*c*) it partly screens the bottom of the furnace from radiation, and absorbs some heat from the bottom by radiation, thus keeping it below the temperature at which the ash is sticky."

In the installation at Philadelphia, to be mentioned later, the ash is so fusible that at the bottom of the combustion chamber it forms a viscous liquid, which flows slowly down over the sloping bottom and out through holes at the back into a water-trough conveyor; here, of course, everything is done that can be done to prevent the loss of heat from the slag and keep it as liquid and as little viscous as possible, and the operation

of removal is continuous and automatic, as long as the working conditions are normal. With a coal having an ash of higher melting-point, the whole arrangement for dealing with the slag might have to be altered.

In another installation, where the slag is more viscous and cannot be removed as a liquid, it is periodically broken up, by directing a stream of cold water upon it, and then removed.

The Milwaukee water screen is being adopted in other installations for boilers; it is not, as a rule, practicable, of course, for metallurgical and other furnaces, but the hollow-walled furnace with channels for the entering secondary air is a form of construction that is not limited to boiler furnaces.

The proportion of the total ash collecting in the combustion chamber, and the proportion escaping by the stack, must of course vary with all the circumstances of the installation. In some metallurgical furnaces 60 to 70 per cent. was deposited in the furnace, about 10 per cent. on the objects that were heated, and 20 to 30 per cent. escaped up the chimney. It has been found by careful observation at Milwaukee that from 25 per cent. to 50 per cent. of the ash remains in the combustion chamber; that from 5 per cent. to 12 per cent. of the ash is collected in the second and third pass; that 25 per cent. to 35 per cent. is caught in the base of the stack and from 12 per cent. to 25 per cent. is lost through the stack. This stack emission does not, however, present any serious problem, as the ash thus emitted is a very fine, flocculent powder thoroughly calcined, with no smudge, so that it is not likely that this will ever present any serious problem, though means for entirely eliminating it are being studied.

GENERAL CONDITIONS OF COMBUSTION—REFRACTORY MATERIALS—FURNACE-ROOM

Higher demands are probably made, on the whole, on the refractory materials used in the construction of boiler furnaces by powdered fuel than by hearth firing, especially in water-tube boilers.

The linings suffer in two ways. They are liable to mechanical abrasion, from the continual rubbing against them of the furnace gases laden with particles of coal or ash ; and they are liable to chemical attack and actual solution, if the ash deposited upon them is at such a high temperature as to be liquid. It is then not confined in its action to the outer surface of the lining, but can penetrate into cracks or holes and disintegrate the brick from within. Such an action would naturally tend to be most severe on the floor of the combustion chamber, where the slag would chiefly accumulate ; and the possibility of its occurrence has to be taken into consideration where coal having ash of low melting-point is used, and where it is proposed to remove the ash in the form of liquid slag. The chamber floor will there have to be protected, either by a thick coating of the slag itself, so thick that the under surface, in contact with the brick, will be solid, or by a thinner coating of some other refractory material upon which the slag will not act chemically.

The qualities needed in a refractory material are : "refractoriness" —that is to say, high melting-point and consequent resistance to softening or fusion at high temperatures ; constancy of volume—the material should show neither gradual shrinkage nor gradual exhaustion during continued use ; resistance to sudden temperature change—it should not, either through expansion and contraction, or through cracking or "spalling," crumble, waste, or break down when frequently heated or cooled with the suddenness inevitable in constant work ; resistance to mechanical wear or abrasion and to chemical corrosion.

It is easier to obtain a material good in one of these qualities if the others need not be considered ; naturally, the higher the requirements and the greater their number, the more difficult are they to meet.

In the early days of powdered fuel firing the difficulties caused by failure of the refractory linings of the furnaces were very great, largely because the proper conditions had not been thought out or discovered. High speeds of the current of fuel and air, fierce and cutting flames, were the order of the day, and it was only gradually discovered that these were not necessary, and that with much slower speeds not only was combustion perfect, and economical communication of heat to the boiler tubes

or the material in the furnace better secured, but the wear of the refractory materials was much reduced. Experience has gradually developed other means of protecting the linings of the furnaces: the hollow walls and the water screen in the Milwaukee installations, for example, described in the section on the disposal of ash, not only render the ash suitable for easy removal, but lower the temperature of the wall of the furnace, and hence greatly increase the life of the lining. Through these and similar devices it may indeed be said that the problem has been solved, and that the difficulties in the preservation of the refractory linings of furnaces are no greater with powdered fuel firing than with grate firing.

Gasification of the coal, combustion of the volatile matter and, later, combustion of the coke occur with powdered coal as with coal burnt on a grate; although the interval of time between the beginning and end of the operation is very small, it is yet sufficient to make a sensible difference between the combustion of powdered coal and that of oil or of a gaseous mixture. There must be sufficient room in the combustion chamber to allow of the free forward motion of fuel and air during the time needed to effect complete combustion, and thus the space needed will be greater than would be needed for an equivalent amount of oil or gaseous fuel.

A certain amount of heat is needed to effect the distillation of the coal in the first instance, and this is restored later by the combustion of the products. It follows that the combustion of powdered fuel will be more readily effected in a hot combustion chamber, where this initial heat requirement can be easily met; and in fact high temperature of the combustion chamber does favour and hasten the complete combustion of the coal. This means, of course, a shorter flame-path, and therefore a hotter flame, when the chamber is hot.

Rapidity of combustion is also heightened by fine grinding, and different lengths and intensities of flame, which may for different purposes be necessary, can be attained, or their attainment can be facilitated, by regulating the fineness of the fuel. As the coarseness of the fuel increases, however, whilst the time needed for burning, and therefore the length of the flame, increases, the tendency of the particles, owing to their weight, to fall out also increases, or the distance to which they can be kept

suspended decreases, so that a limit is soon reached in this direction, beyond which complete combustion will not be possible.

In most cases fine grinding is desirable, though it may not be necessary, but it is costly; the practical limit to very fine grinding, and consequently very short and very hot flame, is the need for avoiding damage to the refractory lining of the furnace.

Actually, furnace temperatures reach 1600° to 1700° C. Refractory materials which are in other respects suitable for building boiler furnaces should not be exposed to a temperature higher than 1550°. American experience indicates that brickwork has a very short life if the percentage of carbon dioxide in the flue gases is more than 15 or 16 per cent.

The combustion chamber temperature in boiler furnaces depends on the relation between the size of the flame and the heating surface: increased load on the heating surface tends to raise the temperature. The ratio of the radiated heat to the total heat is higher the higher the ratio of the size of the flame to the heating surface. It falls with increased load on the heating surface. The amount of radiated heat utilised obviously depends also upon the shape of the combustion chamber, which should be built so as to allow as much free radiation to the heating surface as possible.

The chamber should be large enough to allow of complete combustion with a gentle speed of flame, say 6 to 8 (7 feet, Frion) feet per second, calculated on the whole cross-section. Higher speeds mean more rapid destruction of the brickwork, and tend towards incomplete combustion. If we are considering equal weights of different coals, the coals yielding greater volumes of gas will need more space than those yielding less. A furnace built for one coal may not work so well with another, though probably this applies less to powdered coal than to grate firing.

For the best effect, the temperature must be as near as possible to the theoretical maximum. The flame must burn thus, and must be proportioned to the dimensions of the furnace or combustion chamber (or these must be proportioned to the flame). These conditions can be secured when powdered fuel is used. The flame can be altered in length by varying the speed of entry of coal or air, and in form by varying the

form or the number of the burners. In boilers the flame must not be brought into contact with the tubes, or the rapid cooling may produce premature extinction, and consequent waste of fuel, deposit of soot and smoky chimney.

In boilers, American practice seems to have shown that 2 lbs. of coal per hour is as much as can be successfully and economically burnt per cubic foot of combustion space in boilers ; in metallurgical furnaces much more, up to, say, 9 or 10 lbs. per hour, according to the requirements of the furnace, is possible.

Each lb. per hour per cubic foot is equivalent, assuming a coal of calorific value of 12,000 B.Th.U., to a little over 3 B.Th.U. per cubic foot combustion space per second.

Barnhurst, in a paper read before the Cleveland Engineering Society, states that the general practice is to allow 40 cubic feet of combustion space per lb. of fuel burnt per minute, which is $1\frac{1}{2}$ lb. per cubic foot per hour ; this is equivalent to nearly 5 B.Th.U. per cubic foot per second, with coal of calorific value of 12,000 B.Th.U.

Savage, in a paper quoted elsewhere in this volume, speaking of the tests of the Oneida Street plant, says :

"It is to be supposed that a study of these tests will naturally bring forth two questions : first, 'Why were they all run at such uniformly low ratings ?' and second, 'What has become of the high ratings that have been so much talked of in connexion with powdered coal firing ?'

"First—these tests were all run at the Oneida Street plant at Milwaukee, where the structural limitations were such as to prevent the construction of a favourable type of mixing-oven furnace for any but nominal ratings, and where the area of the steam outlet and a restriction through the superheater header prevent the carrying away of the steam at high ratings.

"Second—as to high ratings, it is true that as yet they have not been forthcoming, but it must be taken into consideration that at present only three plants have been designed for powdered coal—namely, the Ford Motor Company, St Joseph Lead Company and the Lakeside plant of the Milwaukee Electric Railway & Light Company. The first of these has

not yet started powdered coal operation, and the latter two are just starting, but the preliminary tests on the latter two indicate that the much talked-of high ratings with high efficiencies are an accomplished fact. The other plants were all converted from stoker firing, and not being built originally with high ratings in view, either structural or mechanical limitations prevented securing the maximum results that otherwise could be expected from powdered coal firing, although the results, both as to capacities and efficiencies, have been uniformly higher in each converted plant than was possible to obtain with the previous method of firing. It has been shown, by various tests, that capacity is in direct proportion to furnace volume, and that, in the furnaces upon which it has been possible so far to make determinations, the most efficient rates of combustion have been at from 1 to 1·5 lb. per cubic foot of furnace volume, although efficiencies change very little in a properly designed furnace up to 2 lb. per cubic foot and satisfactory operating results can be secured at from 5 lbs. to 2 lbs. per cubic foot, which permits a very wide operating range. Even in this unfavourable type of furnace, at a rate of 1·81 lb. per cubic foot, an efficiency of 78·8 per cent. was secured. Assuming a rate of combustion of 1·75 lb. per cubic foot, the Lakeside furnace, which has a volume of 8000 cubic feet, will burn efficiently 14,000 lbs. of coal per hour. Assuming the coal to have 12,500 B.Th.U. and operating at only 77½ per cent. efficiency, this would be equivalent to 4000 h.p. on these 1308 h.p. boilers, or approximately 300 per cent. rating. At 2 lbs. per cubic foot, the rating would be practically 350 per cent.

"High rating, with high efficiency, is a matter of correct furnace design and furnace volume, which does not necessarily mean a larger volume than that required for the best stoker practice, when ash-pit area is counted as a part of the stoker furnace, but the furnace must be so designed as to permit the flames the longest possible travel through the furnace with low velocity."

EXAMPLES OF VARIOUS APPLICATIONS OF POWDERED FUEL

Powdered fuel has found application through a very wide range of usefulness. Not only in cement manufacture, in which the conditions are specially favourable to its use, since the whole length of the rotary kiln is available for the combustion of the fuel, and the ash can mix with and melt into the clinker without doing any harm ; but in firing limekilns ; in metallurgical furnaces of various kinds ; in steam-raising, both in stationary boilers and in locomotives, and even on shipboard ; and to a small extent even for domestic heating, powdered fuel has been applied. In many of these applications it has been extraordinarily successful ; in others it has failed to yield any advantage over the methods of firing previously in use, and has been re-displaced by those methods. But it is only fair to the new method of firing to point out that in many instances where it has been installed and been taken out again after a longer or shorter interval of time it has not had a fair chance. The conditions governing the combustion of powdered coal have not been studied in these instances, and it has been introduced into furnaces built for other modes of firing without any change or modification ; and there is little doubt that careful study of the problem beforehand, and careful adaptation of the arrangements for firing to the idiosyncrasies of the method, might frequently have turned failure into success.

A short account of some of these applications follows. No attempt at completeness has been made ; but enough has probably been said to indicate, from uses which have been successful, what arrangements would be likely to succeed in any other meditated application. Accounts of a number of other individual installations will be found both in Mr Harvey's report to the Fuel Research Board and in Mr Herington's book.

METALLURGICAL FURNACES

The Canadian Copper Company applied powdered fuel to a reverberatory furnace in which copper ores, especially fines, are reduced

to matt. This furnace, about 116 feet long and 23 feet wide, is fed with ore all along both sides from a series of pipes leading out of troughs on the top of the furnace, into which the ore is brought by travelling cars delivering from the bottom. The effect of this mode of charging is to line the wall of the furnace along its whole length with ore, and thus to protect the brickwork most effectively from the action of the flame. It smelts about 400 tons of ore per twenty-four hours. There are five burners at the end of the furnace, each delivering 19 lbs. of coal per minute. The use of this furnace has enabled great saving to be made in fuel, the ratio of charge smelted to fuel used having been raised from about four to somewhere between six and seven; and a great advantage has further been found in the continuity of the operation and the absence of breaks in the temperature curve due to cleaning of the hearth. The history of the development of this furnace is given in a paper by D. H. Brown in the *Proceedings of the American Institute of Mining Engineers* for 1915, which is reproduced in full in Mr Herington's book.

"The operation of firing," says Dr Brown, "being purely mechanical, comes under the immediate and direct control of the furnace foreman, and responds instantly to his regulation. There is no doubt that reverberatory smelting along these lines will become cheaper than blast-furnace smelting, and that a wider range of ores can be used in such a furnace than in the old coal or oil furnace."

Powdered fuel has since found wide application in the copper-smelting industry, in furnaces similar to this one.

In reverberatory malleable iron heating furnaces, powdered coal can be applied in the same way as in these copper-smelting furnaces. The furnace here is of course much shorter—only about one-fifth of the length—and the burners are arranged in a row of five or six at the end of the furnace. By appropriately sloping the burners the flame can be directed downwards upon, or along, the surface of the metal to be melted; and the high radiating power of the luminous flame causes the rise of temperature of the metal to be very rapid. The rate of rise of temperature can be still further increased if the secondary air is preheated, and the ultimate temperature also raised, so that the flow of metal is facilitated. The ash

gives no trouble here, because it melts down with the slag, and probably renders that more liquid. The ready control of the atmosphere, too, with powdered coal is an advantage; it can be kept on the reducing side, and the loss of metal by oxidation, or the alteration of its composition by the selective oxidation of individual constituents, practically eliminated.

In open-hearth steel furnaces also powdered coal presents certain advantages. Here too, by appropriately arranging the slope of the burners, and by adjusting the pressure of the air and hence the speed of entry of the mixture, the flame can be directed upon the work; and in some of the American furnaces a combination of the ordinary low-pressure burners with a high-pressure burner working at 60 to 80 lbs. per square inch is used. The high radiating power of the flame is also of service here. As the highest temperature is developed close to the metal, the brickwork of the furnace is less severely tried than when working with producer gas.

Much difficulty has been found in working open-hearth furnaces with powdered coal, through the deposition of ash in the chequer-work of the the regenerators, the openings in which it gradually fills and chokes. Some alleviation has been effected by lengthening the down-take flues so that more of the ash shall settle there; and very fine grinding has been recommended so that that portion of the ash which does not so settle shall be as far as possible carried right through to the chimney shaft. But the difficulty, with the use of regenerators, has not been wholly overcome; and C. J. Gadd, in an important paper (*J. Franklin Inst.*, 1916, clxxxii. 347), which recapitulates all that had been done in the United States up to that date, describes the application of powdered fuel to an open-hearth furnace in which there is no regeneration and no reversal of the flame. He says: "The burners are arranged only at one end of the furnace, the path of the flame being always in one direction. There are no regenerative chambers, air at room temperature being used for combustion of the fuel. The theory underlying this method of applying powdered coal to open-hearth furnaces is *first*, the fuel is burned above the bath and all the heat contained in the coal is instantly developed in the furnace. *Second*, as the path of the flame is in one direction, all parts

of the furnace are maintained at the same temperature. *Third,* by reason of their high radiating capacity, the infinite number of minute incandescent particles in the powdered coal communicate the heat by radiation, and not by convection, thus eliminating the necessity of bringing the surrounding air to the temperature of the coal particles. *Fourth,* all the heat in the waste gases is conserved and used in the production of steel.

"The extra fuel consumed, owing to the use of cold air, is offset by: *first,* the elimination of all loss in the gas producer process. *Second,* the elimination of all loss due to frequent reversals. *Third,* the elimination of all loss in waste heat taken up by the regenerative chambers. *Fourth,* the elimination of the expensive maintenance cost of producer plant and regenerative chambers. *Fifth,* by the greatly reduced first cost of installation."

At the time when this paper was read four 50-ton basic open-hearth furnaces thus arranged had been in use for some months. In this short period operating conditions had demonstrated the soundness both of the underlying theory and the engineering principles involved in this method. Compared with producer gas, equally high temperatures were attained. Uniform temperatures throughout the furnace were maintained, and heats could be made within reasonable time. The fuel consumption was high, but this was offset by the fact that the waste-heat plant produced an average evaporation of $6\frac{1}{4}$ lbs. of water per lb. of coal fired into the furnace. Compared with the best boiler-room practice, $62\frac{1}{2}$ per cent. of the fuel consumed by the furnace is used in the generation of steam, leaving $37\frac{1}{2}$ per cent. chargeable to steel production. Based on this reasoning, economies over oil and producer gas are fully substantiated.

Harvey, in his report to the Fuel Research Board, quotes a number of figures from American users of powdered fuel in open-hearth furnaces, in which the fuel consumption is given as from 500 to 600 lbs. of powdered coal per ton of ingots cast; and gives more than one instance in which the output of the furnace in a given period was considerably increased by the substitution of powdered fuel for producer gas.

Mr N. C. Harrison, of the Atlantic Steel Co., in a paper in the *Journal*

of the American Society of Mechanical Engineers, in 1919, says that in powdered coal open-hearth furnaces the coal is delivered into the burner pipe by screw conveyors from the burner bins in the usual way. The burners use a combination of compressed air at 60 to 80 lbs. pressure with air at about 8 oz. pressure from a fan. The hearth is the same as that of any other open-hearth furnace, but the uptakes are as small as possible, so as to hold the gases as long as possible in the furnace, and the slag pockets are large, so as to reduce the speed of the gases going through them and allow as much as possible of the ash to be deposited there. For this reason removable pockets should be used, and frequently cleaned out. There should be one large chequer chamber at each end, built in such a manner as to leave flues of at least 5 inches by 9, and all the passages from the slag pockets to the stack must be as straight as possible. The coal should be as high in volatile matter as possible, and very finely ground, so as to secure quick combustion; there should be 6 or 8 feet between the burner mouths and the bath. The fuel consumption is low; the furnace is under complete control; the flame is hotter than that from producers using the same coal; the finished steel is quieter in the moulds, being less oxidised. The furnaces in the Atlantic Steel Co.'s plant have been more often shut down than the producer fired furnaces through chequer difficulties, and the refractory costs have been greater; but both of these troubles are lessening with longer experience. The coal used is 500 lbs. per ton of steel, against 510 lbs. (hot metal) and 739 lbs. (cold metal) for producer gas; and the cost per ton 0·975 dollar against 1·00 or 1·46 respectively.

Messrs Edgar Allen & Co. Ltd., of Sheffield, have installed a turbo-pulveriser in a reheating furnace for a 500-ton press, which uses slack of various descriptions, instead of the hard coal with which the furnace was formerly hand fired (see Fig. 37), and give the following account of it:—"The ingots are all of hard quality, such as 1·00 carbon, nickel-chrome, chrome-manganese, high speed, and manganese steel, and in size are 10 to 11 inches octagon or square by 10 to 12 cwts. in weight. The furnace has to be cooled at the finish of each shift before such hard steel can be charged, which does not improve fuel consumption figures. The ingots

are usually cogged into 3-inch-square billets, and occasionally into round bars of 6 or 7 inches diameter. The slack used, from half-a-dozen different sources, varies in ash-content from about 22 to 27 per cent., and in moisture from 4 to 12 per cent. The dryness necessary for satisfactory pulverising and firing depends upon the physical nature of the coal used. If spread on the shop floor in a layer of 2 to 3 inches deep it dries quickly enough to supply the press with 6 to 7 tons of hot ingots per eight-hour shift. This spreading is the duty of the fireman and causes no extra work, as he avoids the usual coal firing. The ash from the burnt fuel is deposited in the furnace flue and in the fire-box; the fire-box is raked out after every shift (as in a coal-fire furnace) and the flue about every twelve shifts. Some ash is deposited on the furnace hearth and on the ingots, in amount not much exceeding that resulting from an ordinary coal fired furnace, and varying in quantity according (apparently) with the design of the furnace. For example, one furnace with a hearth 6 feet wide by 10 feet long collects a considerable quantity, whereas another furnace 4 feet 6 inches wide by 14 feet long collects practically none, the ash passing over into the flue. A temperature of 1430° C., to weld wrought-iron plates, can be attained, but the usual practice is 1100° to 1150°. A feed of 300 lbs. of slack per hour maintains this temperature; of course the consumption of fuel per ton of steel is dependent upon the production per hour or shift. Thus, when forging 10-cwt. ingots into 7-inch-diameter bars, 3 ingots are forged per hour, being 200 lbs. of slack per ton. When cogging ingots into 3-inch-square billets the production is less, and 400 lbs. of slack is required per ton.

"At the present date the price of slack averages 10s. per ton, hard coal being 23s. The furnace can be raised to forging heat in four hours from the cold state, as against six to seven hours with hand firing.

"Taking all expenses into consideration—*i.e.* the slack, the motor, fitters' wages, wages for cleaning flues, and interest on original cost of the machine—the result of using the pulveriser has been to reduce the cost of heating ingots by one half."

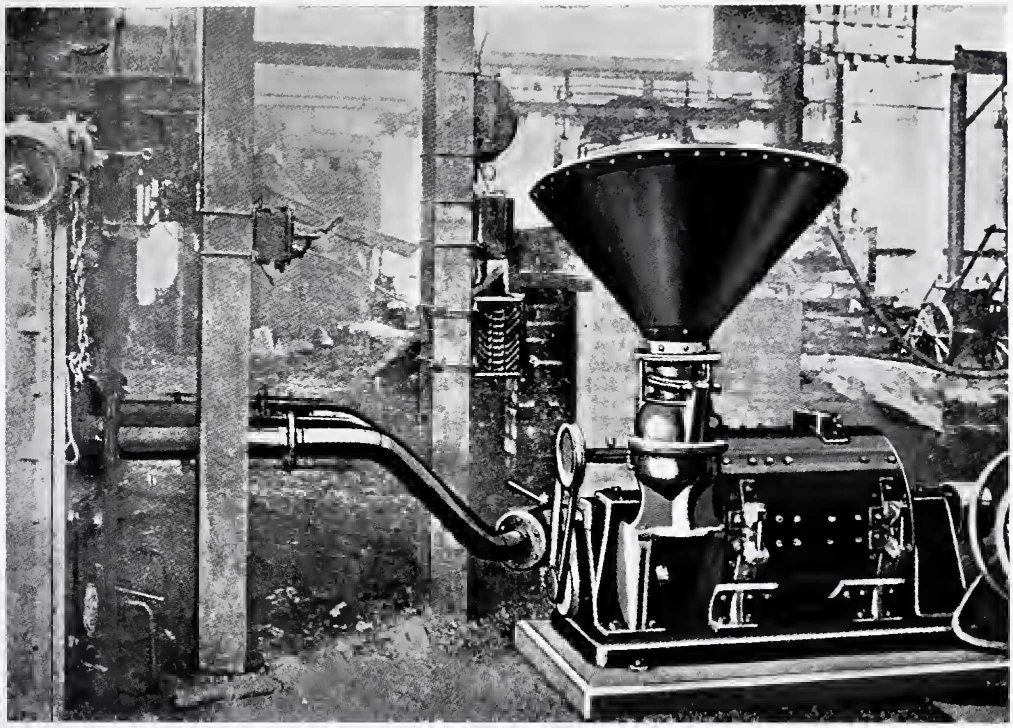

Fig. 37.—Reheating Furnace fired by a Turbo-Pulveriser

The advantages of powdered fuel firing in this furnace are summarised in a report by the forge manager on seven months' work of the furnace as follows :—

"Much less time is needed to heat up the furnace from the cold state; with hand firing at least six hours were needed with this furnace to heat up from the cold; with powdered fuel it can be heated up in three hours. When a shift is finished the pulveriser also finishes; there is not a quantity of coal left burning in the fire-box as is the case with a hand fired furnace. Perfect combustion takes place, so that less fuel is used, and the ash resulting is actual ash, very different from the partially burnt cinders from an ordinary fire grate when the bars are cleaned. Low-priced slack can be used instead of expensive hard coal. The only control necessary is that of air supply and speed of feed, accomplished by a few turns of a small wheel."

In the *General Electric Review* for 1915 Mr Mann gives an interesting account of trials made upon somewhat similar furnaces. In these furnaces the hearths were 43 inches long and 24 inches deep. The flame was introduced high in the furnace, was deflected by the furnace arch, and returned along the hearth bottom to the front, where a flue took it down to the ground level, and then to the back of the furnace, whence it went to the chimney shaft. Through the horizontal flue went a number of iron tubes through which the air for combustion could be introduced and preheated on its way to the burner. The work of these furnaces was so satisfactory that the same design was used for furnaces of twice the area of hearth. The trials were made to ascertain the effect of preheating the air, and also to compare powdered coal firing with oil firing, for which the furnaces were also adapted. Mr Mann says: "We had eleven billets 4 inches square and about 20 inches long, weighing approximately 91 lbs. each, and the two furnaces selected could each heat one half of them at a charge, five at one time and six at the next. As soon as six were heated to a forging temperature just short of dripping they were hauled out and the five cold ones put in. The hot billets were dropped into water and kept there till cold; and the charges were heated alternately all day. Fuel was weighed, furnace temperatures were measured, and to allow for metal

burnt away it was weighed at the beginning and close of each trial to give an average. The Table gives the results of these trials. The first was upon No. 4 furnace with cold combustion air and coal-dust; the second upon No. 0 furnace with hot air and coal-dust; the third with oil on No. 0 furnace. No. 4 furnace is somewhat larger in area than No. 0. The first and second trials may be compared to show the effect of preheating the air; the second and third to show the input of coal and oil:

RESULTS OF FORGE FURNACE TRIALS

	Powdered Coal	Powdered Coal	Oil
Duration of trial	7 hrs. 30 mins.	7 hrs. 37 mins.	7 hrs. 34 mins.
Temperature of furnace at start	Cold, 16 hrs.	Cold, 16 hrs.	Cold, 16 hours
„ „ finish	1370° C.	1355° C.	1350° C.
Average furnace temperature	1300° C.	1301° C.	1270° C.
Time to end of first heat, including bringing up furnace	94 mins.	85 mins.	98 mins.
Number of heats	8	10	9
Average time of each heat, neglecting first	51 mins.	41 mins.	44 mins.
Temperature of combustion air	16° C.	334° C.	240° C.
B.Th.U. per lb. of fuel	14,000	14,000	19,400
Total fuel, including kindling	1042 lbs.	790 lbs.	518 lbs.
Total steel heated	4288 lbs.	5015 lbs.	4563 lbs.
Hourly Quantities			
Lbs. of steel heated per hour	573	659	604
Lbs. of fuel per hour	139	104	69·5
Economic Results			
Lbs. of steel per lb. of fuel	4·11	6·35	8·83
B.Th.U. per lb. of steel	3406	2203	2196

"The efficiencies here of coal and oil, as shown by the second and third trials, are virtually the same; but the heats in this class of work are unquestionably better with coal. They were noticeably brighter and softer, and the coal heat appears to be, in the words of the forge smith, more penetrating.

"It is to be noted that in these trials not all the metal was heated that could have been heated. If each charge had been twice as great the output per lb. of fuel and the efficiency would have been nearly twice as

large, for only about 10 per cent. of the fuel in a furnace goes toward heating the charge ; one quarter of the rest goes to heat up brickwork, and the balance goes up the chimney."

Mann in the same paper mentions the accurate control over the furnace which powdered coal firing permits. It was desired to heat

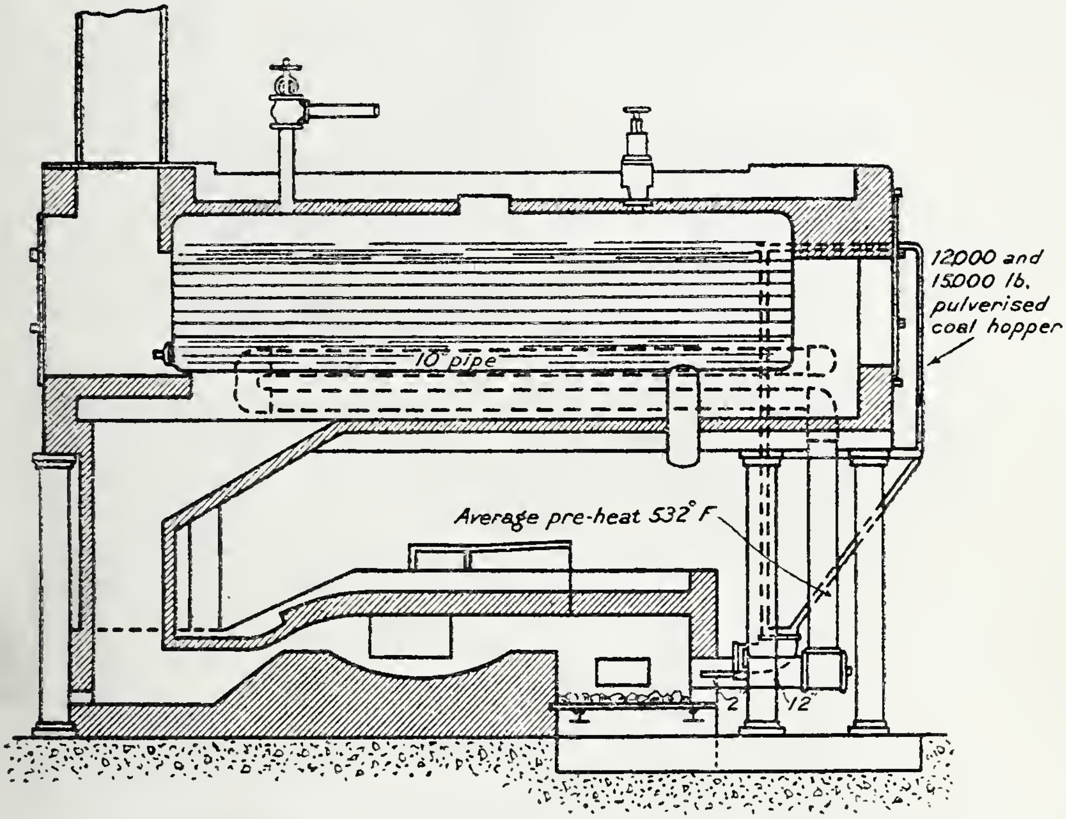

FIG. 38.—PUDDLING FURNACE, WITH WASTE-HEAT BOILER

certain metals very slowly and uniformly, the furnace to be charged cold and brought up to 900° C., the rate of temperature rise not to exceed 200° C. per hour at any time. After reaching 900° C. the heat was to be held for the rest of the day. It was done very easily with powdered coal, and there would have been no trouble in holding a temperature increase of 20° per hour had it been required. This was true of the first hour, too, which presents the greatest difficulty.

In America powdered coal has found very wide application in puddling furnaces. The diagram (Fig. 38) shows a puddling furnace with a

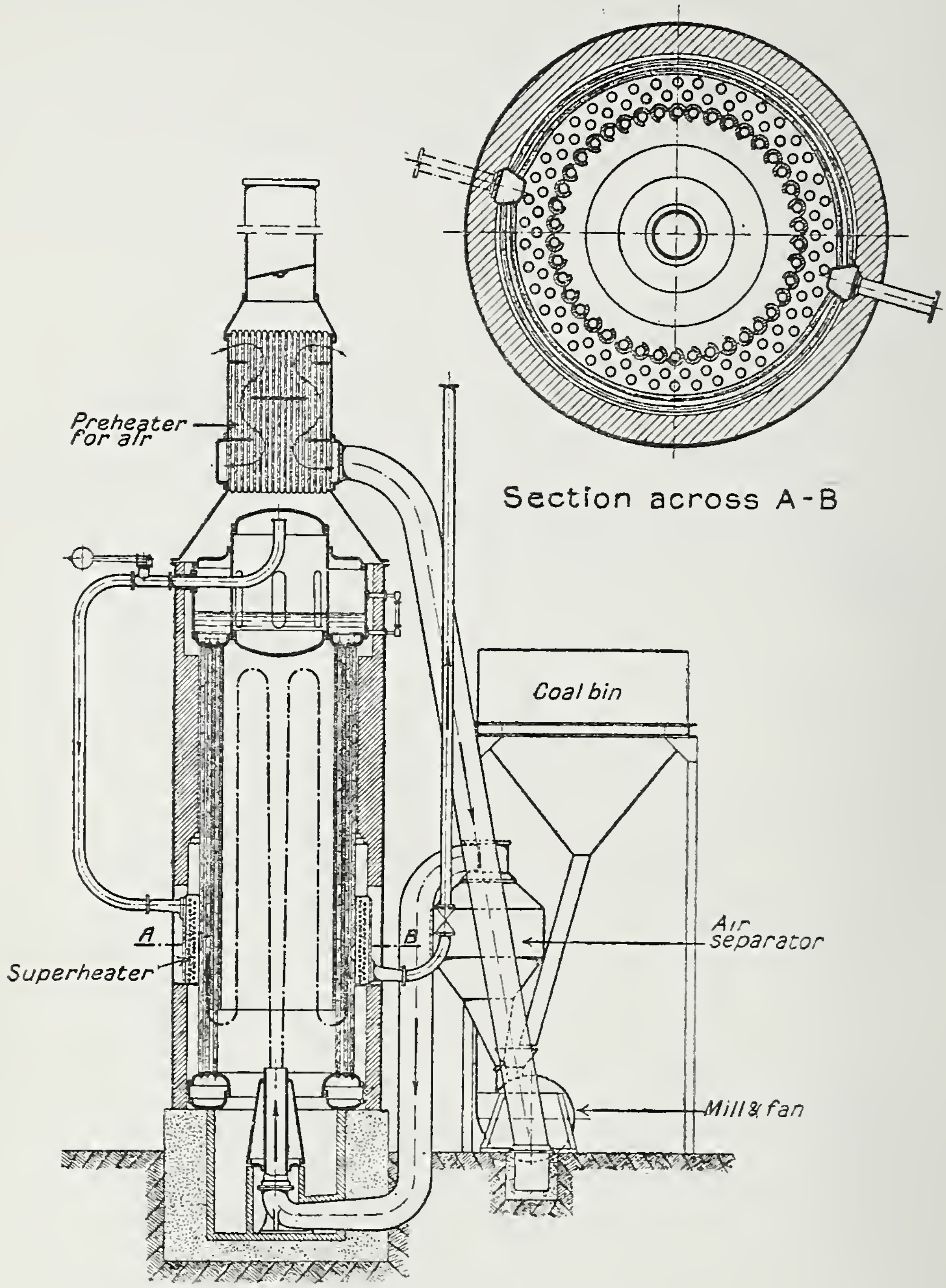

FIG. 39.—BETTINGTON BOILER

waste-heat boiler and an arrangement for preheating the air supply. Tests with this furnace showed the coal consumption per ton of iron produced to be 1025 lbs. with preheated air, and 1146 lbs. with cold air. Harvey, in his report, quotes 1200 to 1600 lbs. per ton for powdered coal firing against 2200 to 3300 for hand firing; and Gadd, in the paper quoted earlier, says that a saving of 30 to 36 per cent. of the fuel is effected by using powdered fuel instead of hand firing. There is further the advantage of the easier and more thorough control of the nature of the flame which can be attained with powdered coal. Objections have been raised to the use of powdered fuel in puddling furnaces on the ground of the deposition of ash upon the work, and the difficulty of getting rid of it; but this does not seem to be a real obstacle in actual practice.

A variety of furnaces of other kinds have been fired with powdered coal successfully; but no good purpose will be served by their enumeration, and they involve no different principle or method of application. Detailed accounts of a number of them will be found in Mr Harvey's report, and in Mr Herington's book.

STEAM RAISING

The boiler devised by Bettington, of Johannesburg, is among the earliest of successful powdered coal fired boilers. It was designed for the express purpose of utilising poor, ashy coals. The pulveriser, fan and boiler form a unit, and, as in other unit systems, the coal is burnt without any preliminary drying.

The boiler (Fig. 39) consists of concentric rows of vertical tubes, terminating at the low end in an annular chamber and at the upper end in a drum. The innermost ring of tubes has a lining of semicircular firebricks, and the outer shell of the casing is also lined with firebrick. Around the bottom portion of the outer ring of tubes goes an annular superheater, through which the steam passes from the drum, and in the flue immediately above the drum is a tubular air heater, through which the air for combustion is drawn by the pulveriser fan. The heated air,

besides recovering heat from the flue gases, dries the coal to some extent as it passes through the pulveriser, and lessens the risk of clogging the screen.

The fuel and air are blown in vertically upwards, and are deflected downwards, along the firebrick lining, when they meet the drum. They curve around the bottom of the tubes, then travel up among the tubes, around the drum and through the air heater to the chimney. This shell of hot gases heats the stream of fresh fuel and air coming from the burner, raises the temperature and quickens the rate of combustion. The vertically impelled particles of coal travel through the combustion chamber twice, and have thus a longer path through the heated zone than would be the case with horizontal projection : and coarser powder can thus be burnt than would otherwise be the case. For the most part the combustion is over at the end of the upward path, and only the larger particles burn in returning. Only very coarse particles are so heavy as not to reach the drum, and may because of their shorter path fall with the ash coked, but not consumed : with good grinding there should be practically no carbon in the slag. The boiler is very flexible, can be heated up with great rapidity, and worked at considerable overload. Banking losses are practically nil, so that for intermittent work the boiler is especially suitable.

The following figures are taken from a paper by King (*Jour. Soc. Chem. Ind.*, 1917, xxxvi. 114). They were yielded by a test which was run for $5\frac{1}{2}$ hours on normal load, 12,000 lbs. of steam per hour, and then for $2\frac{1}{2}$ hours on a 30 per cent. overload. During each test the boiler worked very steadily, the individual figures taken each half-hour hardly varying at all from the average.

	Normal Load	30 per cent. Overload
Pressure of entering air . .	9.8 c.m. water	11.5 c.m. water
Steam, lbs. per sq. inch . .	160.1	161.2
Flue gas entering air heater .	323° C.	330° C.
Flue gas leaving air heater .	290° C.	300° C.
Air entering heater . . .	40.8° C.	42.8° C.

	Normal Load	30 per cent. Overload
Air leaving heater . .	177·4° C.	185·4° C.
Temp. of fuel mixture .	68·1° C.	63·4° C.
Temp. of feed water . .	44·2° C.	55·2° C.
Temp. of saturated steam .	180° C.	175° C.
Temp. of superheated steam .	288·6° C.	287° C.
Flue gas, carbon dioxide .	11·3%	10·9%
Flue gas, carbon monoxide .	none	none
Flue gas, oxygen . . .	7·0%	7·5%
Per cent. loss in flue gas .	16·8	17·9

The fuel used was slack, containing 22·7 per cent. volatile matter, 1·6 per cent. moisture, 13·8 per cent. ash, and having a calorific value of 11,500 B.Th.U. The clinker contained no unburnt carbon; the motor used 48·1 and 53·4 amperes at 44 O.V.

Coal used, total . . .	65 cwts.	31 cwts.
Coal used per hour . .	1344 lbs.	1736 lbs.
Water evaporated, from and at 100° C. per hour .	9·15 lbs.	9·53 lbs.
Boiler efficiency . . .	76·9 per cent.	80·0 per cent.

At the Philadelphia power station of the Lambton & Hetton Coal Co. Ltd., in the county of Durham, a turbo-pulveriser has been fitted to one of a series of boilers, the rest of which are fired by chain-brake stokers. The arrangement of the plant is shown in the photograph, Fig. 40. It burns a local splint coal, which is not easily marketable, because of its hardness and the amount of ash which it contains, running from 20 to 33 per cent. It is hardly practicable to burn this splint upon grates at all, unless it is mixed with some other and better coal. The following are the figures of a test taken on this boiler :—

Total heating surface of boiler	5764 sq. ft.
Total heating surface of superheater . .	1864 ,,
Duration of test	6 hours

Coal—

Total quantity consumed		14,400 lbs.
Average consumption per hour		2400 ,,
Calorific value		9550 B.Th.U.
Analysis	Moisture	0·93 per cent.
	Volatile matter	24·67 ,,
	Fixed carbon	41·24 ,,
	Ash	33·16 ,,

Evaporation and Steam Quality—

Total evaporation	87,740 lbs.
Hourly evaporation	14,623 ,,
Average steam pressure	180 lbs. per sq. in.
Average steam temperature	512° F.
Average steam superheat	132° F.
Average steam feed water temperature	142° F.
Heat added per lb. of steam	1163 B.Th.U.

Gas Temperatures and Analysis—

Average furnace temperature	2560° F.
Average temperature before superheater (last 2 hours only)	963° F.
Average temperature after superheater (last 2 hours only)	846° F.
Average temperature of boiler outlet (over 6 hours)	566° F.
Average carbon dioxide	15·5 per cent.
Average carbon monoxide	0·95 ,,
Average oxygen	1·3 ,,
Actual evaporation per lb. of coal	6·09 lbs.
Equivalent evaporation per lb. of coal, from and at 212° F.	7·30 ,,
Heat per lb. of coal	7083 B.Th.U.
Boiler efficiency	74·1 per cent.

It was estimated by the makers of the pulveriser that had an economiser been in use the plant efficiency would have been increased by from 9 to 10 per cent.

Fig. 40.—Boiler fired by a Turbo-Pulveriser

The following set of combustion tests was also made on this plant :—

Time	CO_2	O_2	CO	Draught Boiler Front	Flue Gas Temperature
				in.	Degrees Fahr.
11.25 . .	16·8	0·6	nil	0·05	490
11.40 . .	16·0	2·2	nil	0·05	500
12 noon .	15·2	2·5	nil	0·05	487
12.30 . .	16·4	1·8	0·5	0·04	446
12.55 . .	16·5	1·5	0·3	0·04	430
2.30 . .	15·9	2·0	nil	0·06	440
2.50 . .	12·5	6·9	nil	0·02	442
3.10 . .	10·9	...	...	0·4	435
3.45 . .	17·0	1·5	nil	0·07	440
4.15 . .	14·7	4·3	nil	0·04	430

NOTE.—At 12.20 P.M. combustion was intentionally arranged to be incomplete. Between 12.55 P.M. and 2.30 P.M. normal conditions were restored, and at 2.45 P.M. an attempt was made to raise the superheat by increasing the speed of gases through the boiler. The boiler damper was raised a further 1 in. At 3 P.M. the damper was raised another 1 in. After 3.10 P.M. the normal conditions of complete combustion were restored.

The ash from the splint coal melts at a temperature of about 1320° C. Most of the ash settles in the combustion chamber in the form of a viscous slag, which has sufficient mobility to run out at the back of the chamber, whence it is taken away in a water conveyor ; but occasionally the slag solidifies and has to be dug out of the furnace bottom. The boiler was not built for powdered fuel, and therefore the circumstances of the combustion chamber are not the most favourable. The combustion is regulated with very great ease, and no smoke is visible from the stack. The ash particles which leave the stack are quite free from carbon.

The general arrangement of pulveriser, burner and combustion chamber in the unit system is indicated in Fig. 41, which shows a Woodeson boiler fired by a turbo-pulveriser ; the almost vertical entry of the burner is seen, and the deep combustion chamber, with sloping bottom for the convenient removal of the deposited ash.

The working of turbo-pulverisers in boiler firing is further indicated by the following tests.

A small Babcock & Wilcox " land " type boiler has been fired at a London works for twelve months; the following tests are typical of its general performance :—

	Sept. 15, 1922 *A*	Sept. 21, 1922 *B*
Heating surface, sq. ft.	2690	2690
Superheater area, sq. ft.	248	248
Duration of test in hours	8	8
Amount of coal used in lbs.	9549	9054
Calorific value of coal (B.Th.U.) as used	10,788	9917
Analysis of coal, ash per cent.	12·8	13·2
Analysis of coal, moisture per cent.	10·7	15·1
Coal burnt per hour, in lbs.	1193½	1132
Water evaporated, lbs. total	68,810	60,000
Water evaporated, per lb. actual, in lbs.	7·20	6·63
Water evaporated, per lb. actual, from and at 212° F., in lbs.	8·5	7·9
Water evaporated per sq. ft. of heating surface from and at 212° F., in lbs.	3·36	2·92
Evaporative factor	1·19	1·19
Temperature of feed water before economiser in degs. Fahr.	106	100
Temperature of gases leaving boiler, degs. Fahr.	484	539
Average percentage of CO_2	12¾	12¾
Steam pressure (average) lbs. per sq. in.	99	96
Temperature of saturated steam in degs. Fahr.	337	335
Temperature of superheated steam in degs. Fahr.	424	431
Efficiency per cent. of boiler with superheater only	77	77·8
Cost of coal for evaporating 1000 lbs. of water	1s. 3¾d.	1s. 0¾d.
*Cost of electric power per ton of coal burnt	2s. 11½d.	2s. 11½d.
Evaporative power of fuel as used, in lbs.	11·13	10·19

* This plant is in London and therefore the cost of electric power is somewhat high.

Note.—It was not possible to measure the efficiency of the economiser during the test. This would have added at least another 10 per cent., making the over-all efficiencies 87 and 87·8 per cent. respectively.

Perhaps the most important large installation of boilers fired by powdered coal—certainly that in which its capabilities have been most thoroughly tested and developed—is at the Oneida Street station of the Milwaukee Electric Railway & Light Company at Milwaukee. This consists of five Edge Moor boilers, each of 468 nominal h.p., and was equipped

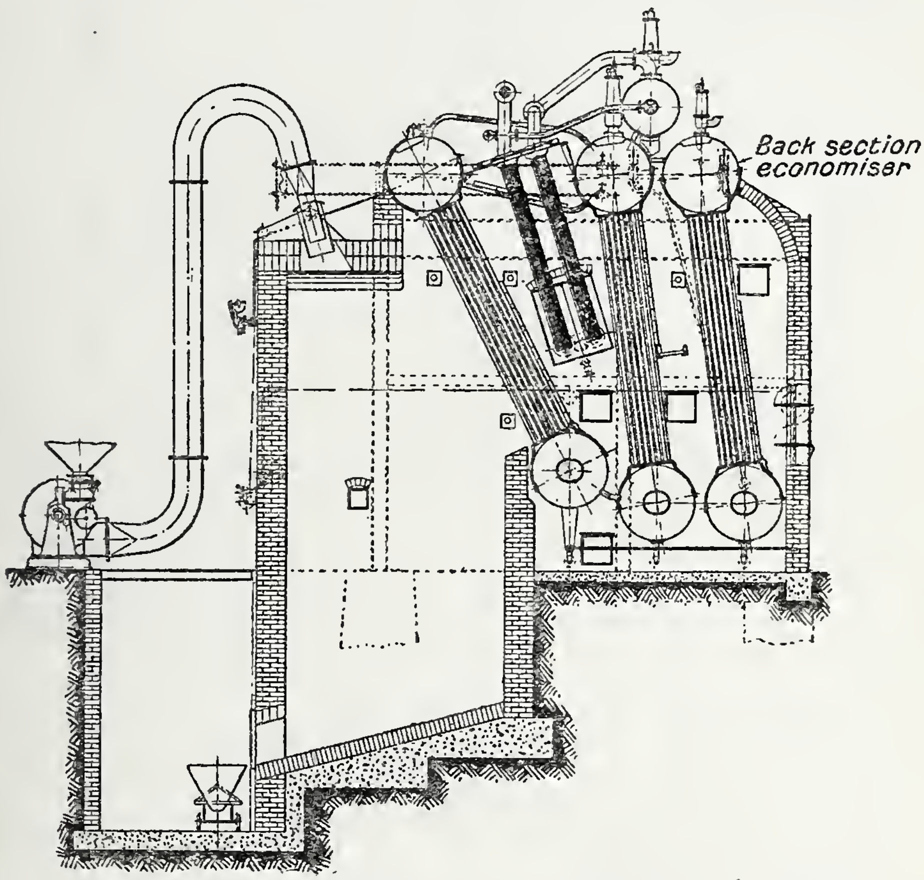

Fig. 41.—Turbo-Pulveriser firing a Woodeson Boiler

in 1918. The following account of it, and of the tests of it which were made on behalf of the Bureau of Mines, is taken chiefly from a paper read before the American Iron and Steel Institute in May 1921, by Mr H. D. Savage. This plant, which is a combined heating and power plant, the principal load being the heating load, has been in operation for nearly three years. No unusual operating difficulties of any kind have been encountered. There have been no interruptions to service due to its powdered coal operation and the plant has met every requirement,

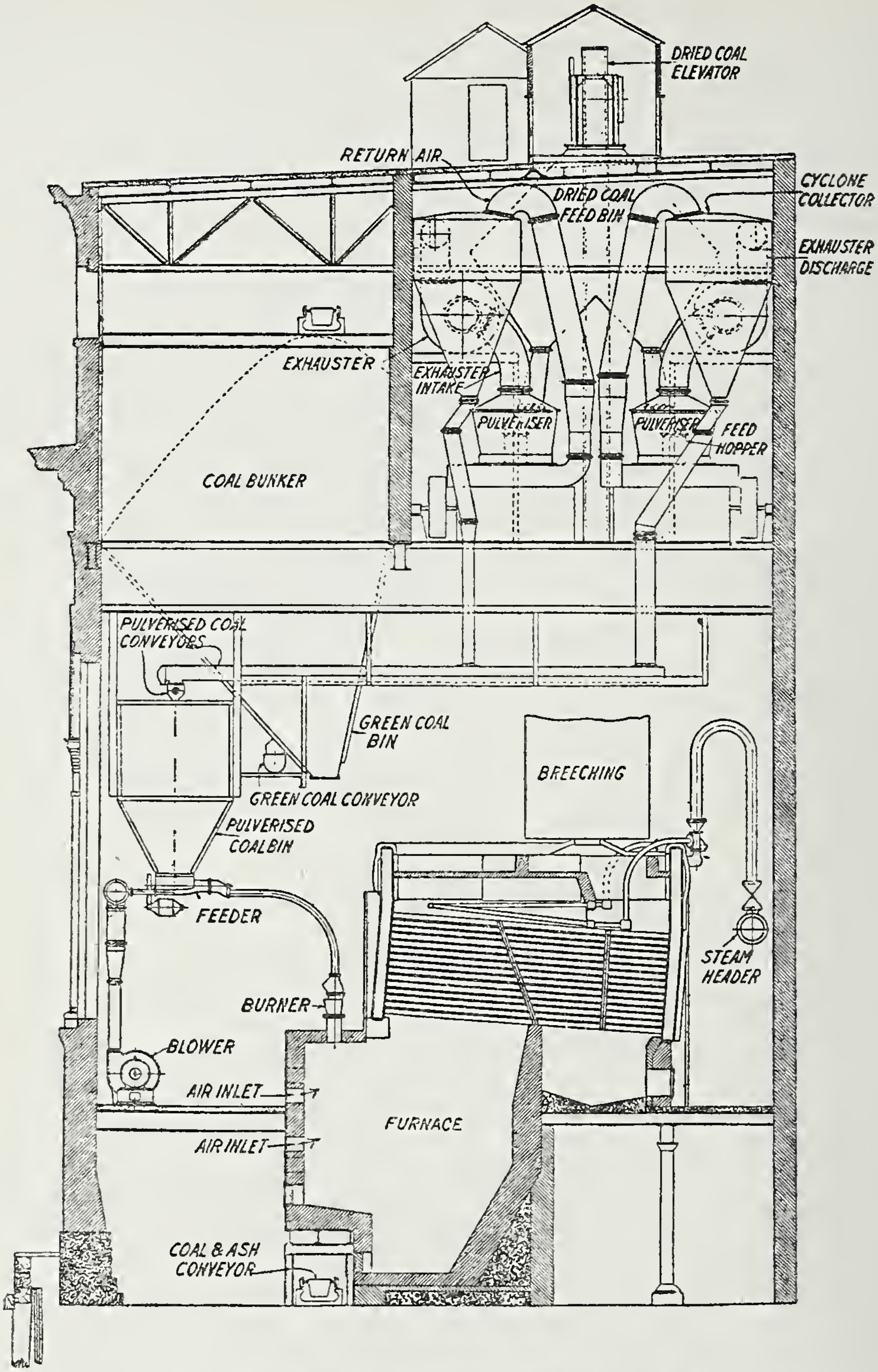

Fig. 42.—Oneida Street Power Station, Cross-Section through Boiler Plant

including the very severe winter of 1919-1920. The importance of the plant is indicated by the fact that it heats practically all of down-town Milwaukee. This plant illustrates the ease with which local conditions can be met in making powdered coal installations. By reference to Fig. 42 it will be noted that the preparation plant was installed over the boilers in a room originally intended to house the economisers.

The statements and conclusions which follow are either based on observation of actual operating conditions, or are taken from test data compiled by Mr H. Kreisinger, formerly of the United States Bureau of Mines, who has been making a series of tests and investigations at the Oneida Street plant of the Milwaukee Electric Railway & Light Company covering a period of some ten months. A summary of eleven tests recently completed at Oneida Street is given herewith (see Table, pp. 122, 123).

The tests were made by the Fuel Section of the United States Bureau of Mines in co-operation with the Research Department of the Combustion Engineering Corporation. The powdered coal equipment was designed and installed by the Locomotive Pulverised Fuel Company. The coal burned on these tests came from the Illinois coal-field. The object of the tests was to determine what over-all efficiency can be obtained with pulverised Illinois coal under various conditions of furnace operation and different preparation of coal as to degree of fineness and percentage of moisture. The tests were made in a thorough manner, everything being done to make the results accurate and reliable. The pulverised coal was weighed in specially designed tanks placed on platform scales as it was supplied to the furnace. The tests were of 17 to 25 hours' duration.

Tests 28 to 30 inclusive were made with the usual preparation of coal as it is burnt in the plant under ordinary operating conditions. Test 31 was made with the same condition of coal as the three previous tests, but with the furnace provided with a cooling coil over the hearth and along the walls near the bottom of the furnace to facilitate the removal of ash. Tests 32 to 35 inclusive were made with the same furnace arrangement as Test 31, but with the coal pulverised to a lesser degree of fineness. Tests 36 to 38 inclusive were made with the same furnace arrangement as the previous four tests, but with undried coal.

Fig. 43 gives a section through the furnace showing the arrangement of the burner and the cooling coil over the hearth and near the bottom of the furnace. The cooling coil consisted of three lengths of 2-inch pipe over the hearth and two lengths along the side walls and the rear wall. The total surface of the coil was 46 square feet.

Fig. 44 shows the coal-weighing apparatus which was placed between

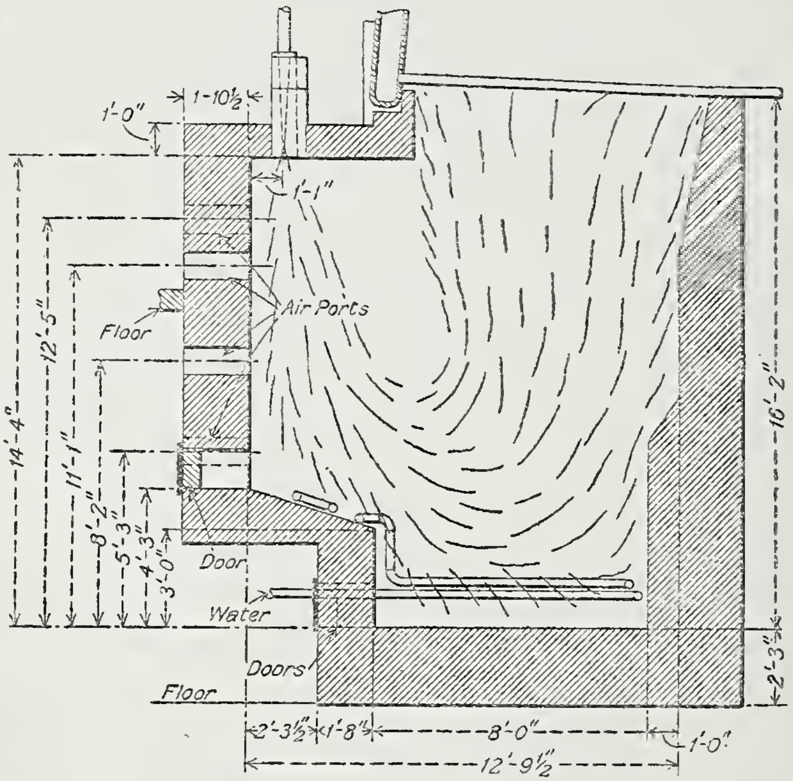

Fig. 43.—Cross-Section of Boiler Furnace used in Tests

the storage bin and the feed bin. There were two burners and two feeders; the coal to each feeder was weighed separately. The weighing tanks were connected to the storage bins and the feeder bin by flexible canvas connexions to permit weighing and to prevent coal-dust from escaping into the room when the weighing tanks were filled and emptied. The tests were started and closed with the feeder bins empty.

The feed water was weighed in two water tanks placed on platform scales. The water supplied to the cooling coil was measured by a 2-inch water meter, which was calibrated at the rate of feeding the water through

the cooling coil, and its measurements were found reliable to within less than one half of 1 per cent.

Flue gas samples were taken at six points in the uptake and collected over one-hour periods. Flue gas temperatures were measured with thermocouples at the same six points where samples were drawn for

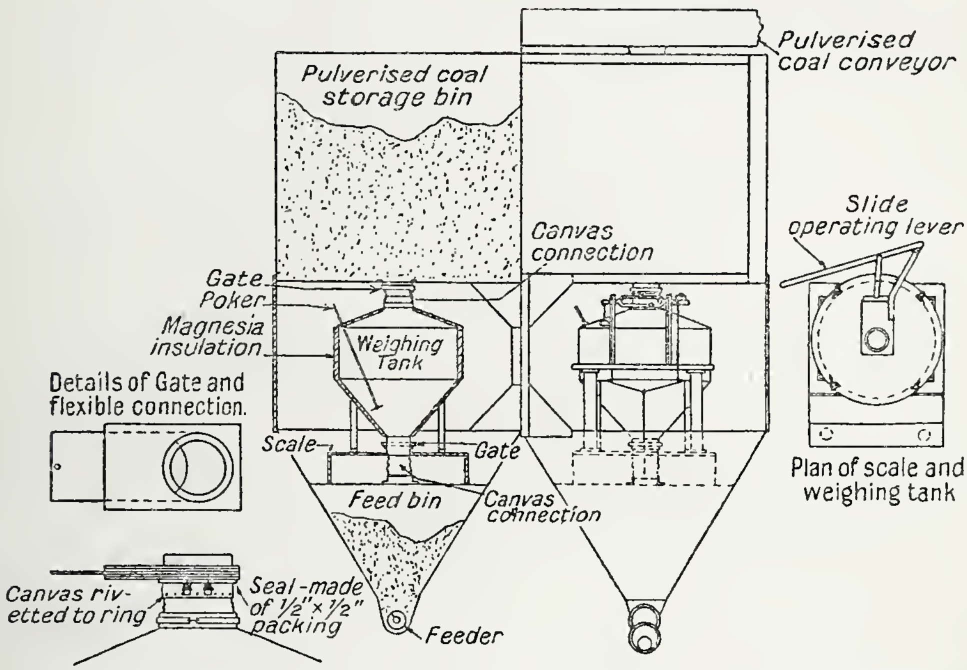

FIG. 44.—ONEIDA STREET POWER STATION—COAL-WEIGHING APPARATUS

analysis, and readings were taken every fifteen minutes. The flue gas temperatures given in the Table on pp. 122 and 123 are the average of the six couples.

RESULTS OF THE TESTS

The results of the tests are given in the Table on pp. 122 and 123. The quantities of heat absorbed by the boiler superheater and the cooling coil, when the latter was used, are itemised separately. In the heat balance the losses by radiation are given as a separate item. In a series of tests on the same boiler and setting, the radiation loss per square foot of exposed surface should be nearly constant and should vary only slightly with the capacity developed by the boiler. For the calculation of the radiation loss it was estimated that 250 B.Th.U. were lost per square foot of the exposed surface

SUMMARY OF RESULTS OF ELEVEN STEAMING TESTS, ON AN EDGE MOOR BOILER, BURNING POWDERED COAL, AT ONEIDA STREET POWER STATION, MILWAUKEE

Heating surface, boiler	4680 sq. ft.	Draft—Natural		Rating of boiler	468 h.p.
Heating surface, superheater	594 ,, ,,	Burner—LOPULCO vertical		Volume of furnace	1600 cub. ft.
Heating surface, furnace coil	48 ,, ,,	Coal Feed—Screw and air blas		Greatest height of furnace	16·7 ft.
				Greatest width	9·3 ,,
Total heating surface	5322 ,, ,,			Greatest length	15·3 ,,

1. Test Number	28	29	30	31	32	33	34	35	36	37	38	
2. Duration, hours	22·90	23·72	18·17	23·62	23·60	22·47	25·22	23·53	23·43	23·33	16·75	Hours
COAL AS FIRED												
3. Per cent. through 100-mesh	96·10	95·80	..	95·40	93·20	93·10	90·80	88·60	..	94·40	95·40	Per cent.
4. Moisture-content, per cent.	1·42	2·92	2·75	2·55	3·79	3·07	3·60	3·47	7·69	8·23	8·23	,,
5. Volatile matter, per cent.	36·62	36·66	37·45	35·58	36·57	36·29	37·17	36·27	35·82	34·42	34·70	,,
6. Fixed carbon, per cent.	48·16	46·63	46·08	48·07	48·43	49·01	46·39	48·87	45·74	46·39	44·67	,,
7. Ash, per cent.	13·80	13·79	13·72	23·80	11·21	11·63	12·84	11·39	10·75	10·96	12·40	,,
8. Sulphur, per cent.	2·66	3·64	3·49	2·92	2·40	2·66	3·43	2·90	2·10	2·21	2·90	,,
9. Calorific value, B.Th.U.	11,956	11,860	11,875	12,085	12,172	12,178	11,889	12,188	11,565	11,508	11,245	B.Th.U.
10. Total fuel fired, lbs.	40,214	39,862	52,746	46,613	43,947	45,469	47,459	41,250	43,729	41,640	36,315	Lbs.
11. Coal fired per hour, lbs.	1,756	1,681	2,903	1,973	1,862	2,024	1,882	1,753	1,866	1,785	2,171	,,
12. Coal fired per hour per cub. ft. of comb. space, lbs.	1·10	1·05	1·81	1·23	1·15	1·26	1·18	1·09	1·16	1·12	1·36	,,
ASH AND REFUSE												
13. Carbonaceous-content in furnace slag, per cent.	0	0	0	0	0	0	0	0	0	0	0	Per cent.
14. Carbonaceous-content in second and third pass refuse, per cent.	4·15	3·49	5·00	5·25	9·52	7·19	7·52	7·37	4·97	4·23	4·49	,,
15. Carbonaceous-content in uptake dust, per cent.	4·95	5·24	7·35	5·13	7·70	6·45	7·81	5·57	3·91	3·50	3·28	,,
16. Calculated total carbon in refuse, per cent. coal fired	0·50	0·54	0·62	0·36	0·87	0·61	0·67	0·30	0·24	0·22	0·26	,,
17. Softening temperature of coal ash, degrees Fahr.	..	2,050	2,210	2,120	2,120	2,110	2,060	..	..	..	..	Degs. Fahr.
ASH ACCOUNT (PER CENT. OF ASH FIRED)												
18. From bottom of furnace	29·20	25·50	41·50	48·10	10·10	24·10	27·80	59·40	48·10	47·10	41·60	Per cent.
19. From second and third pass	12·10	11·60	5·80	10·40	10·30	7·00	9·10	10·50	8·50	7·70	8·70	,,
20. From dust collector	31·50	25·00	33·20	29·20	27·50	29·00	28·50	30·10	32·80	26·00	26·30	,,
21. Unaccounted for	28·20	37·90	19·50	12·30	52·10	39·90	27·60	0·00	10·80	19·20	23·40	,,
AIR												
22. Temperature, air at furnace, degrees Fahr.	83	90	80	76	85	71	64	74	79	72	75	Degs. Fahr.
23. Pressure air at feeder, inches water	5·00	5·30	7·50	5·10	5·60	5·50	6·40	5·90	5·70	5·50	6·20	Ins. water
24. Excess air in flue gas, per cent.	30	22	18	18	19	15	20	25	19	16	20	Per cent.
FLUE GAS												
25. Carbon dioxide, per cent. by volume	24·10	14·90	15·40	15·50	15·30	15·80	15·10	13·60	15·50	15·80	15·40	Per cent.
26. Oxygen, per cent. by volume	4·80	3·80	2·90	3·30	3·20	2·40	3·60	4·10	3·20	2·90	2·60	,,
27. Carbon monoxide, per cent. by volume	0	0	0·26	0	0	0·10	0·10	0	0	0	0	,,
28. Lbs. of dry flue gas per lb. of coal	12·40	11·20	10·60	11·00	11·30	10·89	11·00	11·70	10·70	10·40	10·60	,,
29. Temperature of gases in uptake, degrees Fahr.	517	492	610	483	457	472	470	486	484	466	514	Degs. Fahr.

					DRAFT							
30. At uptake, inches water	0·12	0·10	0·27	0·09	0·06	0·08	0·05	0·09	0·10	0·05	0·15	In. water
31. Top of furnace, inches water	0·00	0·02	0·00	0·00	0·01	0·00	0·01	0·02	0·02	0·03	0·03	,,
					STEAM AND WATER							
32. Steam pressure, lbs. absolute	184	186	196	189	188	187	185	186	183	182	185	Lbs.
33. Degrees superheat	60	59	80	58	53	61	67	79	74	70	102	Degs. Fahr.
34. Temperature of feed water, degs. Fahr.	108	99	99	101	101	100	100	100	103	98	99	,,
35. Temperature of water to coil, degs. Fahr.	No coil			54	53	52	50	48	46	46	46	,,
36. Temperature water from coil, degs. Fahr.	,,			129	146	145	118	151	139	130	144	,,
					RATES OF HEAT ABSORPTION							
37. Per cent. of builder's rating (boiler only)	106·6	103·9	167·4	111·7	102·7	112·4	103·4	104·8	101·9	94·4	113·5	Per cent.
38. Horse-power developed (boiler only)	498·8	486·5	779·0	523·2	480·8	526·0	484·0	490·5	477·0	442·0	531·5	Horse-power
39. Superheater only, horse-power developed	15·8	15·3	32·9	16·3	13·7	15·0	15·4	20·5	18·4	16·3	27·9	,,
40. Furnace coil, horse-power developed	No coil			49·7	55·0	59·7	45·9	17·5*	32·0	29·1	26·8	,,
41. Horse-power developed, total	514	502	812	589	549	691	545	528	527	487	586	,,
					B.Th.U. ABSORBED PER SQUARE FOOT OF H.S. PER HOUR							
42. By water in boiler	3,567	3,482	5,575	3,743	3,437	3,758	3,466	3,508	3,413	3,207	3,798	B.Th.U.
43. By steam in superheating	892	861	1,856	920	772	845	869	1,155	1,039	934	1,573	,,
44. By water in furnace coil	No coil			33,900	37,600	40,770	31,270	33,190	21,910	20,160	18,449	,,
					HEAT ABSORBED PER POUND OF COAL AS FIRED, B.Th.U.							
45. By water in boiler	9,500	9,690	8,990	8,870	8,630	8,710	8,885	9,360	8,560	8.405	8,190	B.Th.U.
46. By steam in superheater	301	304	380	277	246	249	274	391	330	321	430	,,
47. By water in coil	No coil			843	995	988	815	335	575	554	414	,,
48. Total absorbed	9,801	9,994	9,370	9,990	9,871	9,947	9,714	10,086	9,465	9,270	9,034	,,
					HEAT BALANCE, PER CENT. OF HEAT IN COAL FIRED							
					HEAT ABSORBED							
49. By water in boiler	79·4	81·6	75·6	73·4	70·8	71·5	72·4	76·8	74·0	73·0	72·7	Per cent.
50. By steam in superheater	2·5	2·5	3·2	2·3	2·0	2·0	2·3	3·2	2·8	2·7	3·8	,,
51. By water in coil	No coil			7·0	8·2	8·1	6·9	2·7	5·0	4·8	3·7	,,
52. Total and thermal efficiency	81·9	84·1	78·8	82·7	81·0	81·6	81·6	82·7	81·8	80·5	80·2	,,
					HEAT CARRIED AWAY							
53. By dry gases	10·8	9·1	11·4	8·9	8·2	8·6	9·0	9·5	9·0	8·5	9·9	Per cent.
54. By steam from burning hydrogen	4·1	4·3	4·2	4·1	4·1	4·2	4·2	4·0	4·2	4·1	4·2	,,
55. By steam from moisture in coal	0·1	0·3	0·3	0·2	0·3	0·3	0·3	0·3	0·8	0·9	0·9	,,
56. By steam entering with air	0·3	0·3	0·1	0·1	0·1	0·1	0·1	0·1	0·1	0·1	0·1	,,
57. By carbon monoxide	0·0	0·0	1·0	0·1	0·1	0·2	0·4	0·0	0·0	0·0	0·0	,,
58. By carbon in ash and flue dust	0·6	0·6	0·7	0·4	1·0	0·7	0·8	0·4	0·3	0·3	0·3	,,
59. By radiation	2·5	2·6	1·9	2·2	2·3	2·1	2·3	2·4	2·4	2·5	2·2	,,
60. Heat unaccounted for (+ or −)	0·3	1·3	1·6	1·3	2·9	2·2	1·3	0·6	1·4	3·1	2·2	,,
61. Total	100·0	100·0	100·0	100·0	100·0	100·0	100·0	100·0	100·0	100·0	100·0	,,

* Cooling coil in operation during first eight and a half hours of test only.

per hour when the boiler was operated at 100 per cent. of rating, and 305 B.Th.U. when operated at 200 per cent. of rating. The radiation loss was calculated according to the per cent. of rating developed. These calculations of the radiation loss leave the true "unaccounted for," which consists largely of errors. In a series of well-made boiler tests this true unaccounted for should be close to zero and should vary on both sides of the zero-line according to whether the plus or minus errors predominate.

Effect of Fineness.—It has been customary to state that in order to get good results the coal must be pulverised to a fineness of 95 per cent. through the 100-mesh screen and 85 per cent. through the 200-mesh screen. The Table below gives the results of complete sizing tests of the coal burned on Tests 32 to 35 inclusive. The coal was much coarser than specified by the above statement. The results of these tests seem to indicate that it is not necessary to pulverise the coal to the extreme fineness of 85 per cent. through the 200-mesh screen in order to get good combustion and good efficiency. The completeness of combustion seems to be more a matter of proper furnace and burner design and the right way of supplying air than the fineness of the coal. The losses due to coarseness of coal would be shown by the greater percentage of carbon in the refuse. The average loss due to this cause for the four tests with the coarser coal is 0·7 of 1 per cent. The average of this loss for the previous four tests is 0·6 of 1 per cent. The average of the efficiencies is very nearly the same. The ability to burn coarser coal means increased capacity of the pulverising mills and decreased cost of coal preparation.

RESULTS OF SIZING TESTS ON COAL BURNED

Test No.	Size of Coal		Through Screen	
	20-mesh	40-mesh	100-mesh	200-mesh
32	99·9	99·2	93·2	67·0
33	99·9	99·2	93·1	70·1
34	100·0	98·9	90·8	65·5
35	99·8	98·0	88·6	64·0

Effect of Moisture in Coal.—Another statement that has been generally accepted is that coal must be dried to about 1 per cent. moisture in order to be successfully burned in pulverised form. In order to determine to what extent this statement is true, Tests 36, 37 and 38 were run with undried coal. The results of the tests show that the completeness of combustion was as good as with the dried coal. There was no loss due to CO in the flue gases and the losses due to combustible in the refuse averaged only 0·3 per cent. for the three tests, which is in fact less than the average with the dried coal.

The losses due to moisture in coal, of course, increased 0·5 to 0·6 per cent., which increase is at the rate of about 0·1 per cent. for every 1 per cent. of increase of moisture in the coal. The average decrease in the boiler efficiency for the three tests is about 0·7 per cent., which checks closely the increase in the losses due to increased moisture in the coal. It seems, therefore, that it is not necessary to dry the coal down to 1 per cent. of moisture in order to get good boiler efficiency. In fact, it seems that most of the Eastern coals can be pulverised and burned with good results without drying.

The Milwaukee Electric Railway & Light Company had already in 1916 begun the construction of a new power station at Lakeside of 200,000 kws. capacity, to meet the need of increased output; but the war conditions compelled them to give up, and it was not till 1919 that they again set to work with the first section of it, which was to furnish 40,000 kws. The original plans were almost completely changed. Mr R. H. Pinkley, one of the company's staff, in an account of the new station, says:

" This change in plans was largely influenced by the results of experiments in the use of pulverised coal which the Company had been conducting at its Oneida Street plant. In the course of these experiments the utilisation of this fuel had been perfected to such an extent that it was decided to equip the new plant for the use of this fuel exclusively. In the few years that the construction had been deferred by the war the controlling conditions for the lay-out of the plant had resulted in changing it from a stoker plant using Eastern coal delivered by boat to a pulverised fuel plant using Illinois coal delivered by rail; and an entirely new set of

plant had to be developed. . . . The power plant proper is made up of four parts: the switch-house, the turbine-room, the boiler-room and the pulverising-room. The pulverising plant, 108 feet by 125 feet, is east of the boiler-room. It is equipped to prepare the coal for a plant of 80,000 kws. capacity. To the north of the pulverising plant, about 400 feet from it, placed against the side of the bluff to take advantage of the slope to secure a gravity flow for the coal, is the car-dumping and coal-crushing plant from which the coal is carried by a covered belt conveyor to the pulverising plant.

"This Company has had experience with the highest grade of stoker plants and also with the pulverised fuel method of operating boiler furnaces. Recent tests on the boilers equipped for burning pulverised fuel at the Oneida Street station indicated that we could expect better efficiency with pulverised fuel than with stokers. A full report on the comparative results of operating, cost of labour, power and investment was submitted, expressing the advantage of one system over the other in terms of amount of saving as against increase in investment. On this report a decision was reached to design the Lakeside station for pulverised fuel.

"There are eight 1306 h.p. Edge Moor boilers, which operate normally at 250 per cent. of rating. Three are sufficient for a 20,000 kw. turbine, leaving two spare boilers. Each boiler has a Foster superheater, capable of raising the temperature of 90,000 lbs. of steam per hour from 411° to 611° F., and a Sturtevant economiser of 7603 square feet surface, which will raise the feed water from 140° to 255° F. The furnaces are equipped with the Lopulco system of pulverised fuel burning.

"The green coal bunker is in the pulveriser-house, and stores 3400 tons, over three and a half days' supply for the whole of the boilers in the section. Three screw conveyors take the coal to automatic weighing scales, whence it is fed by screw conveyors to any one of the three driers. These driers can take 10 tons per hour each and reduce the moisture from 10 to 2 per cent. Screw conveyors and bucket elevators then take the coal to dried coal bins over the pulverising mills. (The author understands that USCO gravity driers are now being tried in this plant.)

"There are eight pulverising mills, each of 6 tons' hourly capacity, passing 75 per cent. through a 200-mesh and 90 per cent. through a

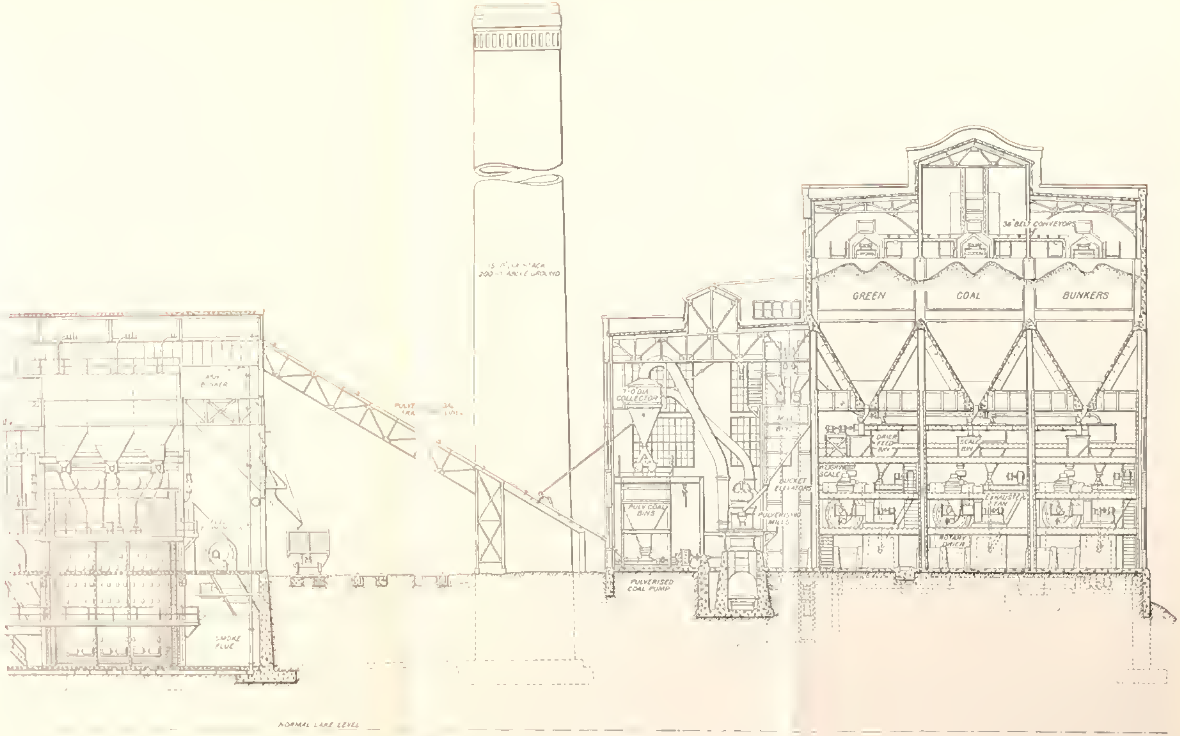

Fig. 45. Lake[illegible] Power Station. General Lay-Out of Powdered Fuel Plant

100-mesh screen. An air-separating fan carries away the fine coal, and discharges it into cyclone separators, whence it goes to the pulverised coal bins. From these it is conveyed to the furnace bins by a Fuller-Kinyon pump. The general lay-out of the plant is seen from Fig. 45.

"The boiler furnaces have hollow walls through which the secondary air is led and preheated, and water screens for cooling the ash and the bottom of the combustion chamber. Mr Kreisinger's description of the construction and working of these devices will be found under 'Ash' on page 93. Fig. 46 is a section showing the general arrangement of the furnace and boiler. The hollow walls and the water screen have proved so effective that they are being introduced very generally in new installations.

"The operation of the plant, which has been continuous since December 1920, has been extremely satisfactory, the plant going into service with an entirely new organisation of men unacquainted to a very large degree with pulverised fuel systems. No difficulties have been experienced and operation has been uninterrupted up to the present time. The economical results so far obtained indicate that there will be no difficulty in reaching the specified thermal efficiency of the station when the installation is complete and the station operated as specified. It must be borne in mind that these results are being obtained using the ordinary grade of Illinois coal. With stoker plants such lower grade coal does not give best results and a comparison of Lakeside plant must of necessity be made with other plants burning Illinois coal if full realisation of the tremendous advantage which coal burned in pulverised fuel form has over stokers is to be brought home to the engineer desiring the best results."

The following descriptions of large plants are given by Mr Savage in the paper before quoted:—

"At the Oklahoma City plant of Morris & Company, the meat packers, there are (see Fig. 47) five 500 h.p. Edge Moor boilers and two 300 h.p. Edge Moor boilers. A distinguishing feature of this plant is the ability to operate the plant on either natural gas, fuel oil, or powdered coal—whichever the condition of the market warrants as being most economical. A change from one fuel to another can be made in about

five minutes. As a matter of fact, the plant has operated almost constantly on powdered coal since its completion. At the time the installation was completed, it was found that when oil was above 90 cents per

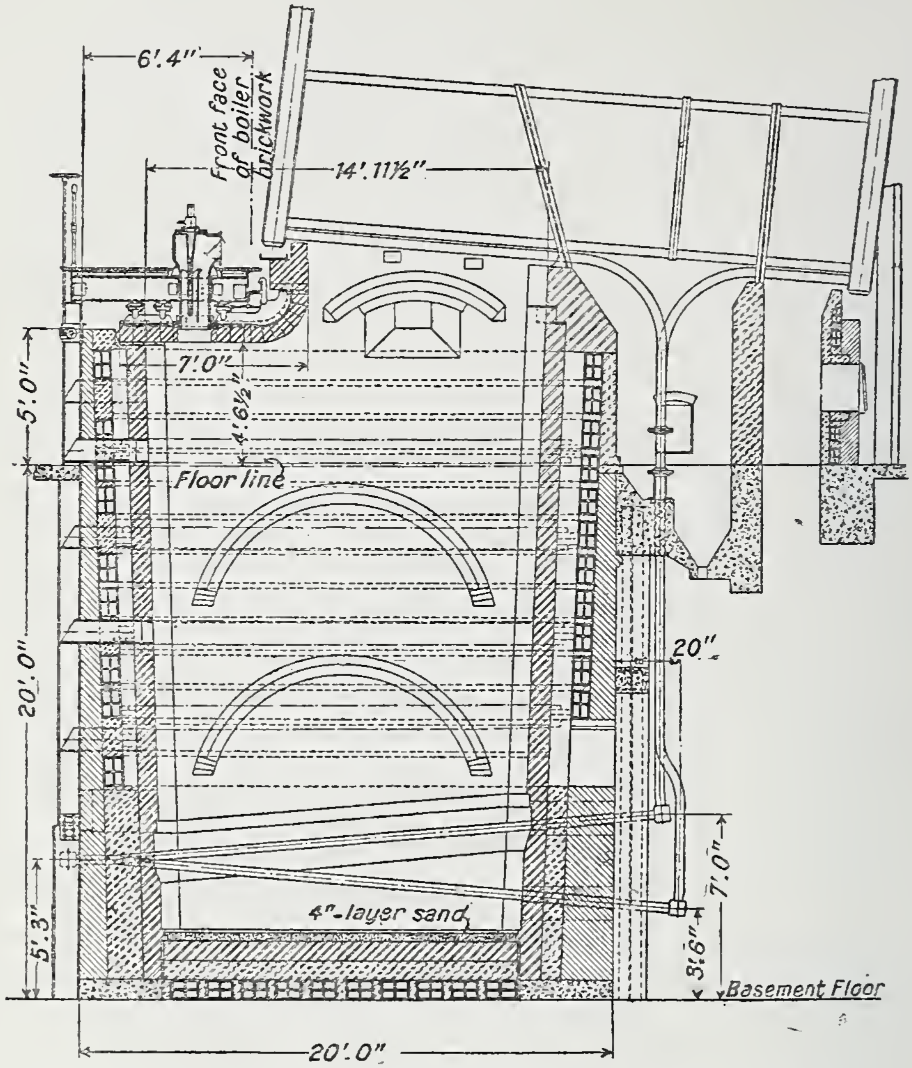

Fig. 46.—Furnace and Boiler Arrangement at Lakeside Power Station

barrel, coal was the more economical. We do not know just where the line of preference occurs to-day, but judge that it is at a higher price for fuel oil. A recent report from this plant, covering the first nine months of 1920, using \$4·13 coal and including a 20 per cent. charge for interest and depreciation, shows a net cost per 1000 lbs. of steam of \$·385.

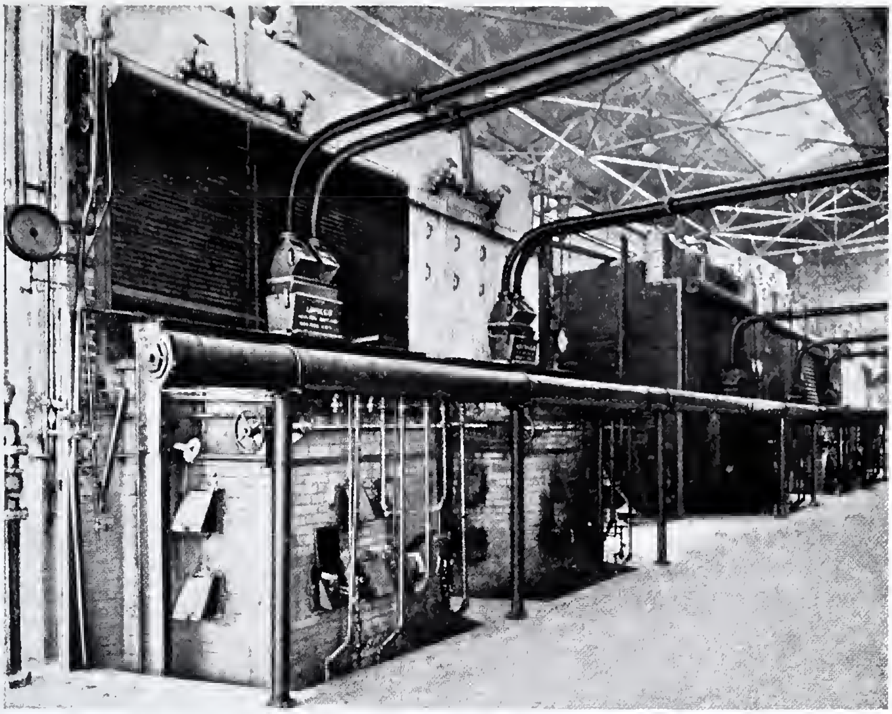

FIG. 47.—OKLAHOMA CITY POWER PLANT OF MORRIS & COMPANY

"Mr Oderman, master mechanic in direct charge of the Morris & Co. plant, has stated in reference to burning oil in these furnaces that 'this is a decided advantage over old-style furnace, as brickwork stands up better; also have less trouble with flues. One test under 468 h.p. Edge Moor boilers showed 14·809 lbs. of water per lb. of oil burned with 110 per cent. of rating on boiler, with boiler efficiency of 77·67 per cent. It is much easier to keep fires clear in the Lopulco furnace than in old-style boiler setting, and one can crowd them to higher rating.'

"One of the most interesting powdered coal applications is just now near completion. This is at the River Rouge plant of the Ford Motor Company, where powdered coal is being installed in connexion with four Ladd boilers of 2640 nominal horse-power each. These Ladd boilers are the largest boilers that have as yet been built and are intended to operate normally at from 200 to 250 per cent. of rated capacity. The boilers will operate on a combination of blast furnace gas and powdered coal and the design is such that these fuels can be used either separately or in combination (see Fig. 48).

"When the preliminary studies were being made in conjunction with the plant, it became apparent, as is usual, that there would not be a sufficiently constant supply of blast furnace gas to maintain the necessary capacity, especially as a large amount of power-consuming equipment, in addition to the blast furnace requirements, would be installed. Therefore the old problem of what fuel to use in combination with their blast furnace gas arose. The Ford Motor Company, realising the importance of this proposition, secured talent of a very high order and turned the problem over to them. The committee conducted a very exhaustive investigation, covering a period of practically two years, to arrive at a correct solution of this problem. The most available and cheapest fuel is usually coal. The problem of using coal on stokers in combination with blast furnace gas, while an old one, has never been satisfactorily solved. Separate stoker fired boilers, in a measure, meet the operating conditions, but they lack flexibility and make first costs and operating costs excessive.

"After a careful study of the combustion characteristics of the various

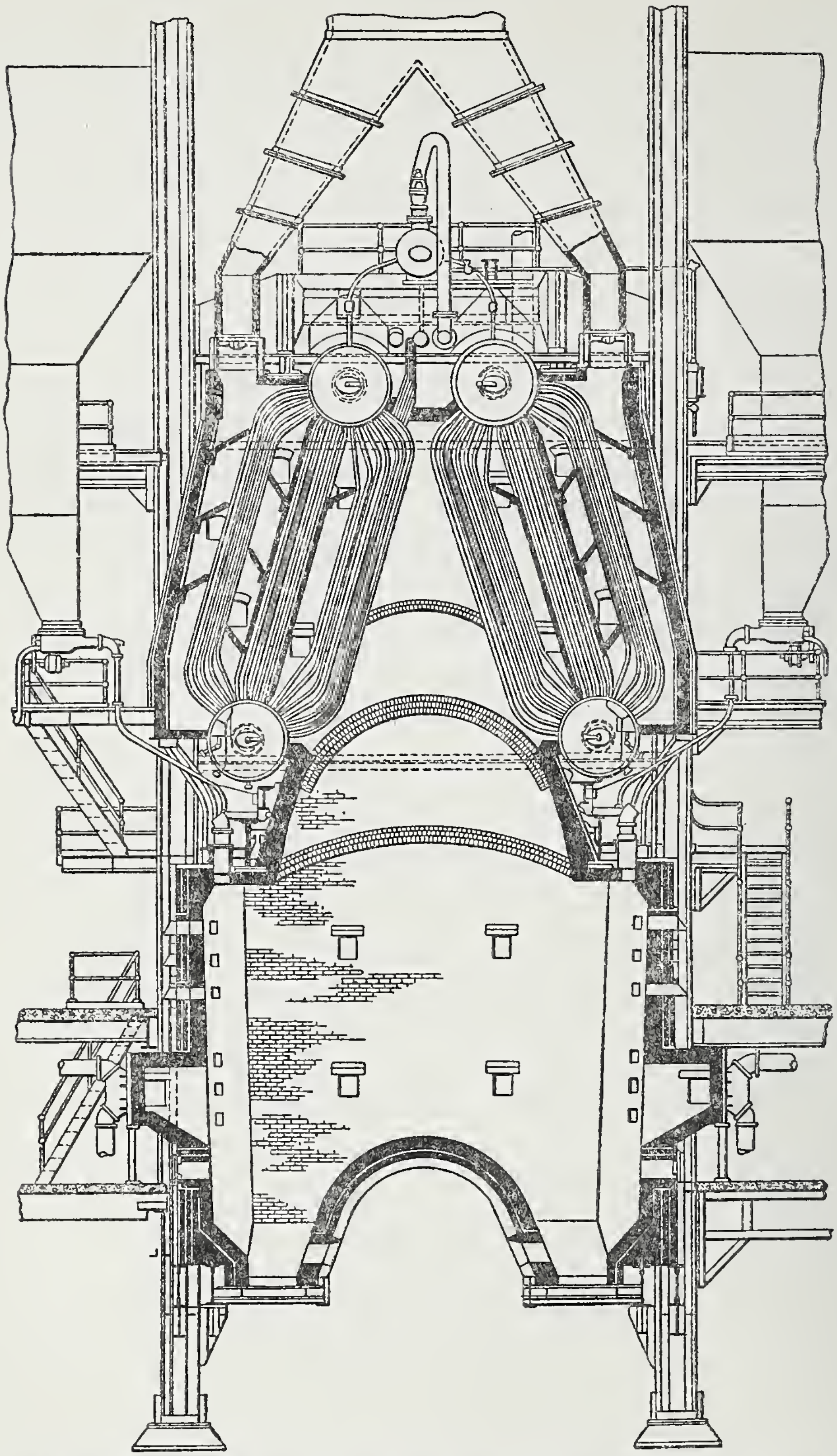

FIG. 48.—CROSS-SECTION THROUGH LADD BOILER INSTALLATION AT RIVER ROUGE PLANT OF FORD MOTOR COMPANY

types of fuels under consideration, it appeared that the conditions governing the efficient combustion of both blast furnace gas and powdered coal were so similar as to make this the only feasible combination. The furnace requirements for the efficient combustion of blast furnace gas seemed to approximate very nearly to the furnace requirements for the efficient combustion of powdered coal.

"This combination, while not as yet actually tried out, would appear to present an ideal solution of this much discussed problem, as powdered coal, when fired as in the present installation, may be considered and handled as a heavy mechanical gas. Much better thermal efficiency than is usually had will be obtained from the blast furnace gas, as the incandescent particles of finely divided ash in suspension in the fire-box will create innumerable zones of high intensity which will aid in the flame propagation of the lower grade blast furnace gas.

"In this installation the gas is introduced horizontally at a lower level than the coal and through the medium of an especially designed grid burner. The results obtained with this burner so far have been extremely satisfactory, as the boilers have been operating on gas alone for several months and ratings of around 175 per cent. have been obtained."

The following data, collected since the original reading of this paper, present some very interesting facts and figures in regard to the operation of this installation covering a period of a year or more:—

APPROXIMATE ANALYSIS OF COALS USED

	Moisture per cent. as fired	Ash per cent.	Volatile per cent.	F. Carbon per cent.	B.Th.U. per lb.	Per cent. through 100-mesh	Per cent. through 200-mesh
May 15, 1921 .	3·9	10·0	12·4	74·8	13,810	89·1	74·8
May 17, 1921 .	7·0	12·3	10·82	76·5	12,630	92·0	76·5
May 18, 1921 .	8·9	22·3	9·5	76·0	12,660	94·0	76·0
May 19, 1921 .	8·4	22·8	5·9	69·0	12,480	88·5	69·0
May 21, 1921 .	3·3	12·3	14·0	70·4	13,300	91·0	72·5
May 25, 1921 .	1·64	17·0	15·1	71·9	13,659	84·0	62·0
May 26, 1921 .	12·06	10·0	15·7	74·3	12,528	84·0	61·0
Feb. 7, 1922 .	2·40	7·30	32·80	57·50	14,158	86·32	66·32
Feb. 9, 1922 .	3·40	8·00	33·40	55·20	13,996	81·44	70·90
Feb. 10, 1922 .	3·78	8·60	31·50	56·12	14,163	85·18	65·92

The average daily coal consumption is about 300 tons. The Table on page 131 gives an idea of the variation in the moisture-content of the coal used. In the process of pulverising the coal loses about 2 per cent. of its moisture. No appreciable change in efficiency follows a change in coal.

The fact that this plant is without driers has eliminated the usual troubles from condensation in the pulverised coal bins. The installation, as mentioned above, has been in operation for over a year, and it has never been necessary to clean out a single bin.

The combination of blast furnace gas and coal has been very economical and satisfactory in every respect. The boilers are generally operated on coal and gas at about 250 per cent. of rating, of which enough gas is used to develop about 75 per cent. of nominal rating.

The furnaces are also equipped for burning tar obtained from the coke ovens. As a general thing the tar is disposed of in other ways, but occasionally, when a surplus of it is produced, it is used in the furnaces.

The furnaces have been operated with a combination of blast furnace gas, tar and pulverised fuel, or any of these fuels separately, or a combination of any two of them. In changing from one fuel to another there is not the slightest delay, and the average observer would not be able to tell when the change takes place.

The gas burners are designed to operate with either forced or induced draught. At the present time induced draught is used.

The boilers normally operate at about 250 per cent. of rating. The load on No. 2 boiler has been up to 410 per cent. of rating, but as the steam could not be used, this rating was maintained for a short while only.

The Park Gate Iron & Steel Company Ltd., of Rotherham, have approached the problem of supplementing the occasional deficiencies, which are always liable to arise suddenly where blast furnace gas is being used, in a similar way, though the scale on which they are working is much smaller than that of the Ford Company. They have two Babcock boilers, each designed to furnish 30,000 lbs. of steam per hour. Each boiler

is fired from the front of the combustion chamber by blast furnace gas through two annular burners of special design, and a No. 4 turbo-pulveriser, capable of supplying 3000 lbs. of coal per hour, feeds two burners which enter the combustion chamber almost vertically at the top, so that the flame impinges on that from the blast furnace gas a foot or two in front of the gas burner mouth. The whole has been designed so that coal or gas separately, or both together, may be used. The installation is recent, and there has not yet been time to obtain complete tests of its working; but so far it has proved entirely satisfactory, and when working with both gas and coal an evaporation of 48,000 lbs. of steam per hour from one boiler has been attained. No difficulty has arisen in the removal of the slagged ash from the bottom of the combustion chamber, and the ash which leaves by the stack seems to be completely carried away and dispersed.

Probably the largest European installation is that for the power station of the Société Anonyme Union d'Electricité, Paris, at Vitry, which is now being constructed on the Lopulco system by the Underfeed Stoker Co. The experience gained in the Milwaukee stations is being utilised here, as will be seen from the section through the boiler-house (Fig. 49), where the hollow boiler walls and air ducts, and the water screen above the combustion chamber bottom are shown. An unusual feature is the waste-heat gravity drier, inserted directly between the coal bin and the pulveriser, and fed with waste gases from the flue in the manner shown.

The initial installation will consist of four Delauney-Belleville boilers, each complete with superheater and economiser, and an idea of its size will be gained from the following data:—

Heating surface of each boiler	16,678 sq. ft.
Heating surface of each economiser	9,684 sq. ft.
Normal hourly evaporation per boiler, from and at 212° F.	140,580 lbs.
Maximum hourly evaporation per boiler, from and at 212° F.	210,870 lbs.
Lbs. of water from and at 212° F. per sq. ft. boiler heating surface per hour, normal	8·4

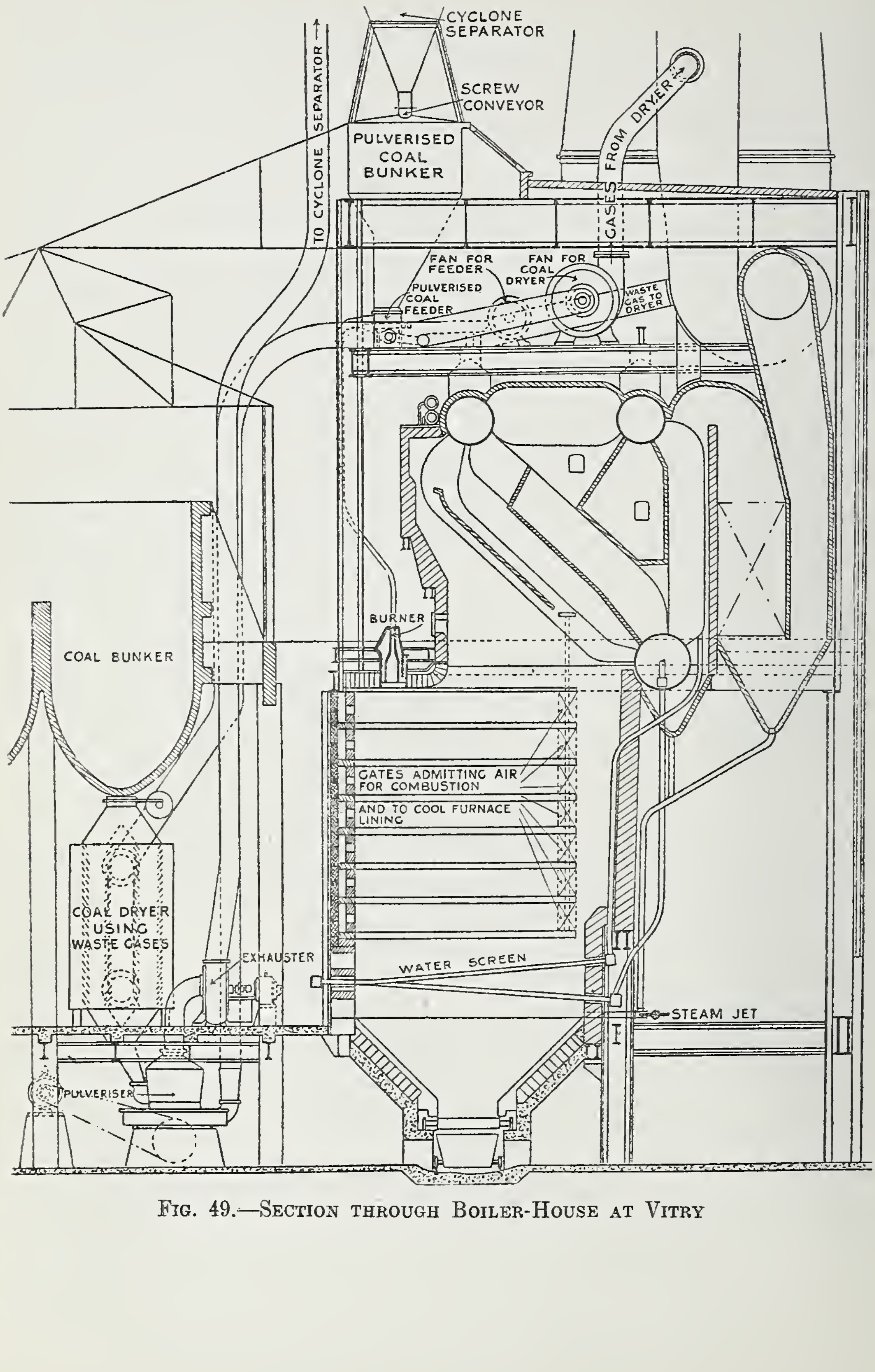

FIG. 49.—SECTION THROUGH BOILER-HOUSE AT VITRY

Lbs. of water from and at 212° F. per sq. ft. boiler heating surface per hour, maximum . . .	12·6
Lbs. of coal to be burnt per hour, normal . . .	12,800
Lbs. of coal to be burnt per hour, maximum . .	19,700
Calorific value of coal on which guarantees are based .	12,600 B.Th.U.

Each boiler will have its pulveriser, with drier, and exhauster to separate the powdered coal and deliver it to the bunker; and five duplex feeders with fans, delivering coal and air to ten burners. The power needed for drying, pulverising and separating the coal, and delivering it to the burners, will not exceed 19½ kw. hours per ton.

LOCOMOTIVES

The requirements of locomotive firing, and the improvements which powdered coal firing may reasonably be expected to produce, are stated by Muhlfeld (*Journ. Am. Soc. Mech. Eng.*, 1916, xxxviii. 983). From a quarter to one-third of the total amount of fuel used by locomotives in the United States is spent in kindling, preparing and maintaining fires on grates when locomotives are standing, drifting or otherwise not using steam to move themselves or trains. A great deal of this would be saved if powdered fuel were used. Mr Muhlfeld says: "The use of powdered fuel should eliminate smoke, soot, cinders, sparks and fire hazards; reduce noise, time for despatching at terminals, and stand-by losses; should increase daily mileage by producing longer runs and more nearly continuous service between general repair periods. It will improve the locomotive by securing continuity of working pressure, greater sustained boiler capacity, increased boiler efficiency, reduced cylinder back pressure, and more highly superheated steam. The excessive rates of evaporation now required can be attained by its use; whilst arduous labour on the part of the stoker will be substituted by skilled control and more assistance given to the driver.

"When coal is burnt on grates a rate of about 50 lbs. of run of mine, or 60 lbs. of lump bituminous coal, per square foot of fire surface per hour, is the maximum allowable for the greatest boiler efficiency. But as this

limits the rate of consumption to a total of 3000 to 6000 lbs. per hour for the average modern locomotive of great power, and as the actual coal supplied to the fire-box by mechanical stoking frequently reaches a rate of 150 lbs. per square foot of grate area, or a total of from 9000 to 15,000 lbs. per hour, the boiler efficiencies frequently run as low as 55 to 45 per cent. or less."

In the *Engineer* for April 1919 Mr J. G. Robinson of the Great Central Railway describes the application of powdered coal to a locomotive. In order to adapt the fire-box, the grate and ash-pan were removed and two openings were made through the water space of the back of the fire-box above the foundation ring and clear of the footplate. "The apparatus for injecting the fuel and primary air to the fire-box is installed on the tender and is steam-driven throughout." The fuel is contained in a hopper, in the bottom of which are placed two horizontal conveyor screws, rotated through gearing by a small steam-engine, which is connected to the feed-screws by a two-speed train of spur gearing, operating worms which drive worm wheels on the feed-screw shafts. The object of the double gear is to ensure that the piston speed of the small engines shall be high enough to prevent undue cylinder condensation losses at the lowest rate of feed. On leaving the feed-screws the fuel is met by a blast of air at a pressure of about 14 inches of water delivered through pipes by a fan revolving at 2500 revolutions per minute. Steam for the engine driving the feed-screws and for the fan turbine is led from the boiler by pipes, the exhausts from both being condensed in a series of pipes in the well of the tender tank, thus allowing a considerable portion of the heat of the exhaust of these auxiliaries to be returned to the boiler, which is fed by a pair of hot-water injectors capable of dealing with water at 140° F. In case of any accident to the turbine or its steam connexions, the fan is provided with a pair of clutches which enable the turbine to be disconnected, the fan being then driven by means of a chain by the engine operating the feed-screws. Thus the locomotive can continue at work in case of any such mishap.

Several locomotives fired by powdered fuel were run experimentally in America immediately before the war. Experience with these showed

that from 45 to 60 minutes is usually enough to get up 200 lbs. steam pressure from boiler water at 40° F. After firing up, the fuel and air supply can be regulated to suit the standing or working conditions, the stack blower being used only when steam is not being used. The ordinary waste of fuel from the stack, and the irregularities produced by opening the fire-door, are avoided by the use of powdered coal, and the approach to uniformity of firing is so near that steam can be regularly maintained within about 2 lbs. of the maximum allowable pressure. There are not many data of the working of powdered fuel fired locomotives available, but one locomotive instanced by Mr Muhlfeld hauled about 10 per cent. more tonnage than a similar locomotive with grate firing. The results with regard not only to tonnage, but also to speed, completeness of combustion and steam pressure, were excellent. Two locomotives, according to a paper in *The Railway Engineer* of 1920, are regularly operated with powdered fuel in America, one on the Lehigh Valley Railway and one at the works of the Fuller Engine Co. at Allentown. The Lehigh Valley locomotive makes a daily trip of about 88 miles on a mixture of 55 per cent. of anthracite silt and 45 per cent. of bituminous coal, and the net saving in fuel cost, allowing for the cost of preparation of the powdered coal, is said to be $1325 per day. The maximum rate of tonnage of the locomotive when hand fired is 900 tons, but when fired by powdered coal it has hauled loads running from 900 to 1080 tons.

In *Engineering*, 1916, cii. 387, an account is given of the operation of locomotives in Sweden, fired by powdered peat. Tests show that for equal boiler duty 1 kilo. of coal, of calorific value 7240 calories, required in substitution 1·45 kilo. of pulverised peat, of calorific value 4400. The peat was ignited by a coal fire on a small grate; this grate consumed 3 to 4 kilos. of coal for every 100 kilos. of peat; and tests made with hand coal fired and powdered peat fired locomotives gave boiler efficiencies of 67 per cent. and 73 per cent. respectively. The peat for these locomotives, as delivered to the pulverising installation, contains 25 to 40 per cent. of moisture, and is dried to 12 or 16 per cent. of moisture; the whole of the pulverised peat used passes a screen having 100 meshes to the sq. cm. (25 to the linear inch).

In Brazil locomotives have been built to use powdered coal and have proved quite satisfactory. One of the main advantages there has been, that in the powdered form native coal can be efficiently used, whilst with grate firing it was impossible to burn it, and all the locomotive coal used had to be imported. In India there is much low-grade coal and

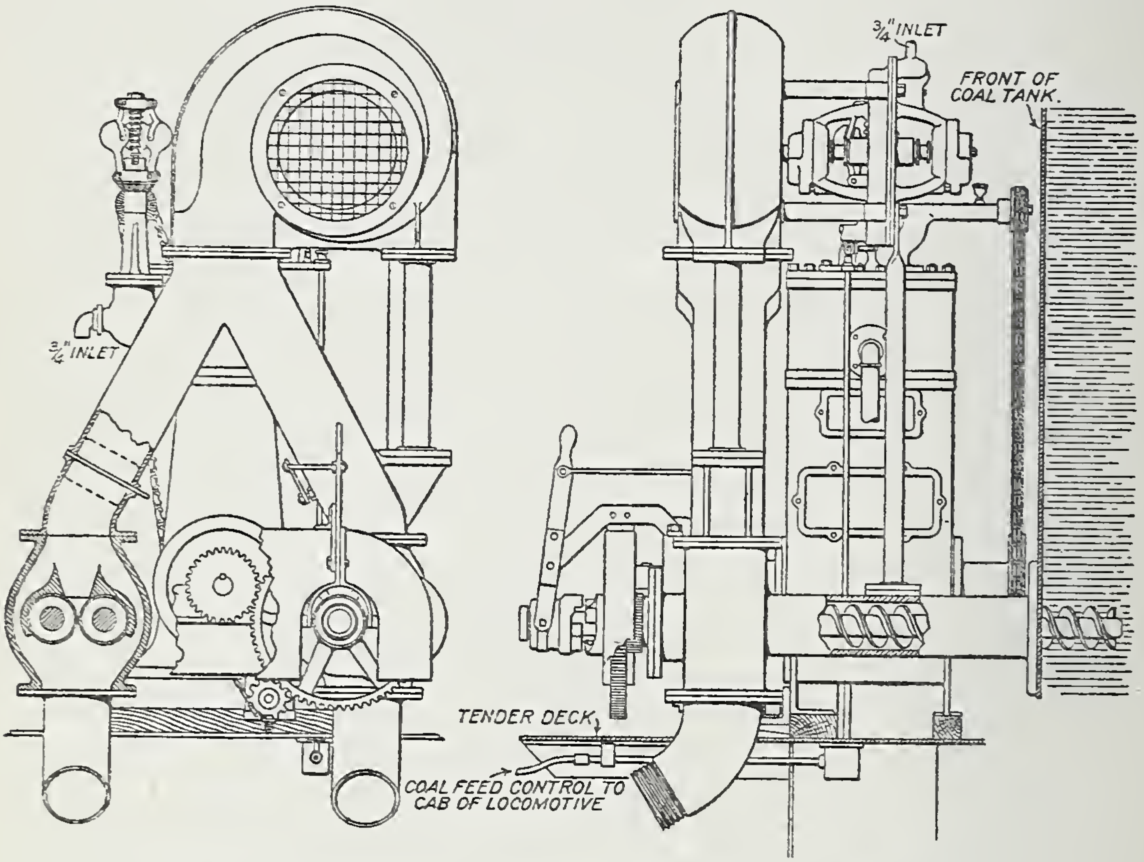

FIG. 50.—FULLER LOCOMOTIVE—FEEDING ARRANGEMENTS

lignite available, and if this could be similarly used for locomotive purposes a very great saving would be effected. The Indian Government Railway Board have appointed an officer to make an investigation into this subject.

In practically all locomotive installations the coal is powdered in a separate plant and stored in the tender, from the bunker in which it is delivered by screw conveyors to the mixing chamber, in which it meets with air on its way to the burner. In Fig. 50 are shown front and side views of the Fuller Company's locomotive plant. The feeding screws, in pairs, on either side, are driven by gearing from the small engine, and

discharge the coal into the enlarged mixing chamber, where the blast of air from the turbine-driven fan mixes with it and carries it on to the burner. A speed variation of the feeder engine and coal feed can be controlled from the cab, and the gear shifts on the feeder permit this range to be doubled, so that the rate of the coal feed can be altered through a very wide range. Two wide flexible hoses connect the feeding tubes with the burner on the engine.

MARINE PROPULSION

A method of using coal on shipboard, combining powdered coal firing with grate firing, was tried by the United States Shipping Board in 1918. Coal was roughly pulverised so that the product varied from dust to pieces a quarter of an inch across ; and this product was blown into the boiler over the grate, on which the usual fire had been started. The fine coal burned, and the heat partially caked the larger pieces, which then settled out upon the fire-bed and were burnt. A free and easily trimmed fire resulted, and the combination possessed to a great extent the flexibility of powdered coal firing.

The question of powdered fuel for marine work is discussed at some length by F. P. Coffin in the *General Electric Review*, 1919, xxii. 200. He suggests the preparation of the coal on shore and its storage on board in the powdered form. The installation of any of the forms of slow-speed grinding mills would be impracticable on account of the space required, but some form of high-speed pulveriser, coupled directly to a motor, might be used. The objection to the storage of powdered coal is of course the large amount of bunker space that would be necessary ; but the bunkering of the ship and the transport of the fuel from the bunkers to the furnace bins would be much less laborious than the corresponding operations with lump coal, and more like those with oil. If turbo-pulverisers or similar unit mills were used, the most economical plan would probably be to crush the coal on shore and fill the bunkers with coal ready for the pulveriser. Mechanical means for the conveyance of such coal from the bunkers to the hopper of the pulveriser could no doubt be devised, so as to reduce

considerably the manual labour required, in comparison with that needed for the firing of lump coal.

The problem of combustion chamber space would be more difficult to solve on shipboard than on land. The large and deep combustion chambers which experience has shown to be desirable and efficient on land would not be practicable for marine work. Very fine grinding and short hot flames seem to be indicated as the only solution, and this would involve special refractory material for the construction of the furnaces. Much experimental work will be needed before this problem can be satisfactorily solved.

Some records of experience in the propulsion of steamships by powdered coal do exist. The U.S.S. *Gem*, a scout patrol with two Normand boilers of 1100 h.p. each, was in 1918 equipped by the Fuller Company for burning powdered coal. Two feeders and two burners were adapted to one boiler (originally oil fired), and a blower for the air. The coal was pulverised on shore and shipped in bags. The burners used 3230 lbs. of coal per hour; there was perfect combustion and no smoke, and a sustained speed of 17¼ knots was developed—better than the work of the same boiler on oil. This was a war-time experiment, and was no doubt costly; but it showed at least that powdered coal firing on board ship is practicable. Harvey, too, in his report, mentions H.M.A.S. *Skylark*, one of the boilers of which was run during the whole period of the war on powdered coal shipped from shore into closed bunkers. Further experiments on marine work will be described under the subject of colloidal fuel.

COSTS

It is difficult to obtain trustworthy figures to show either the cost of installation, or those of working and of maintenance, of powdered fuel plants. The difficulty is the greater because the question cannot be treated generally, but each individual installation must be considered in its conditions and its requirements. The most that can be done is to gather together data from all available sources, and to present them, leaving the reader to exercise his judgment upon them.

Mr L. C. Harvey, in the second edition of his valuable report to the

Fuel Research Board, on Pulverised Coal Systems in America, gives a Table, quoted below in a slightly abbreviated form, through the courtesy of the Controller of H.M. Stationery Office, of the costs of installation and operating costs for powdered fuel plants of different sizes. The figures are revised so as to represent as closely as it can be done the cost at the period of publication (1922). They are based on the following assumptions :—*Labour*.—£4 per man per 44-hour week. *Power*.—1½d. per kw. hour : power for all operations, 20 kw. hours per ton of coal pulverised and delivered to the exit of the mill-house. *Driers* fed with pulverised coal, costing 40s. per ton at the drier burners : amount of coal used, 2 per cent. of the coal dried ; reduction of moisture-content of coal, from 15 per cent. to 1 per cent. *Yearly output* based on 300 working days.

COST OF PULVERISING PLANTS AND COST OF PULVERISED COAL PER TON (2240 LBS.)

Daily Output tons	Labour per ton	Power per ton	Drier Coal per ton	Repairs per ton	Without Stand-by Plant: Mill-house Plant, including Building	Without Stand-by Plant: Interest per ton 6 per cent.	Without Stand-by Plant: Depreciation per ton 10 per cent.	Without Stand-by Plant: Total Preparation per ton	With Stand-by Plant: Mill-house Plant, including Building	With Stand-by Plant: Interest per ton 6 per cent.	With Stand-by Plant: Depreciation per ton 10 per cent.	With Stand-by Plant: Total Preparation per ton	Daily Output tons
	s. d.	s. d.	d.	d.	£	s. d.	s. d.	s. d.	£	s. d.	s. d.	s. d.	
5	5 10	3 0	10½	4	3,500	2 9½	4 8	17 6	...	...	...	...	5
10	2 11½	2 10	10¼	4	6,700	2 8	4 5½	14 1¼	...	...	...	...	10
15	3 11	2 10	10¼	4	6,700	1 9½	3 0	12 8¾	...	...	...	...	15
20	2 11	2 10	10	4	9,300	1 9	2 10½	11 6½	10,300	1 11½	3 3	12 1½	20
30	1 11¾	2 10	10	4	9,300	1 3	2 1	9 3¾	10,300	1 4½	2 3½	9 7¾	30
40	2 2	2 8	10	4	9,300	0 11	1 7	8 6	10,300	1 0½	1 9	8 9½	40
50	1 2	2 8	10	4	11,100	0 10½	1 6	7 4½	12,700	1 0	1 8½	7 8½	50
60	1 0	2 8	10	4	11,100	0 9	1 3	6 10	12,700	0 10¼	1 5	7 1¼	60
70	0 10	2 8	10	4	11,100	0 7½	1 1	6 4½	12,700	0 8¾	1 2½	6 7¼	70
80	1 1	2 6	10	3¾	11,100	0 6½	0 11	6 2¼	12,700	0 7½	1 1	6 5¼	80
90	1 0	2 6	10	3¾	11,100	0 6	0 10	5 11¾	12,700	0 6½	1 11	6 1¼	90
100	0 10½	2 6	9¾	3¾	14,300	0 7	0 11½	6 0½	15,350	0 7½	0 0½	6 2	100
150	0 7	2 6	9¾	3¾	15,000	0 4¾	0 8	5 3¼	18,100	0 5¾	0 9¾	5 6	150
200	0 5¼	2 6	9¾	3¾	20,000	0 4¾	0 8	5 1½	25,500	0 6	1 0	5 6¾	200
250	0 6¼	2 6	9¾	3¾	20,000	0 4	0 6½	5 0¼	25,500	0 5	0 8¼	5 3	250
300	0 5¼	2 6	9¾	3¾	26,100	0 4¼	0 7	5 0	31,600	0 5	0 8½	5 2¼	300
400	0 5¼	2 6	9½	3¾	28,300	0 3½	0 5¾	4 9¾	32,000	0 4	0 6½	4 11	400
500	0 5¼	2 6	9¼	3¾	31,000	0 3	0 5	4 8¼	35,500	0 3½	0 5¾	4 9½	500
600	0 5¼	2 4	9¼	3¾	32,000	0 2½	0 4¼	4 5	37,000	0 3	0 5	4 6¼	600
700	0 4½	2 4	9¼	3½	35,000	0 2½	0 4	4 3¾	41,000	0 2¾	0 4¾	4 4¾	700
800	0 5½	2 2	9	3½	43,000	0 2½	0 4¼	4 2¾	50,500	0 3	0 5	4 4	800
900	0 3½	2 2	9	3½	48,000	0 2½	0 4¼	4 0¾	54,000	0 2¾	0 4¾	4 1½	900
1000	0 3¼	2 2	9	3½	53,500	0 2½	0 4¼	4 0½	59,500	0 2¾	0 4¾	4 1¼	1000

Harvey further calculates out from these figures, from completed costs of transporting and burning the powdered coal, and from the corresponding costs for hand firing, the relative cost for performing the same work by hand firing and by powdered fuel, on the assumption that 75 lbs. of powdered fuel at the burner will be equivalent to 100 lbs. of large coal on the grate. These results are embodied in the following graph, which shows the saving effected per ton of grate-fed fuel when the price of coal is between 20s. and 60s. per ton. The distance between the horizontal line representing the price of coal and the corresponding coal indicates the saving or otherwise effected by substituting powdered fuel for hand stoking in installations having the daily coal consumption shown along the base-line of the graph.

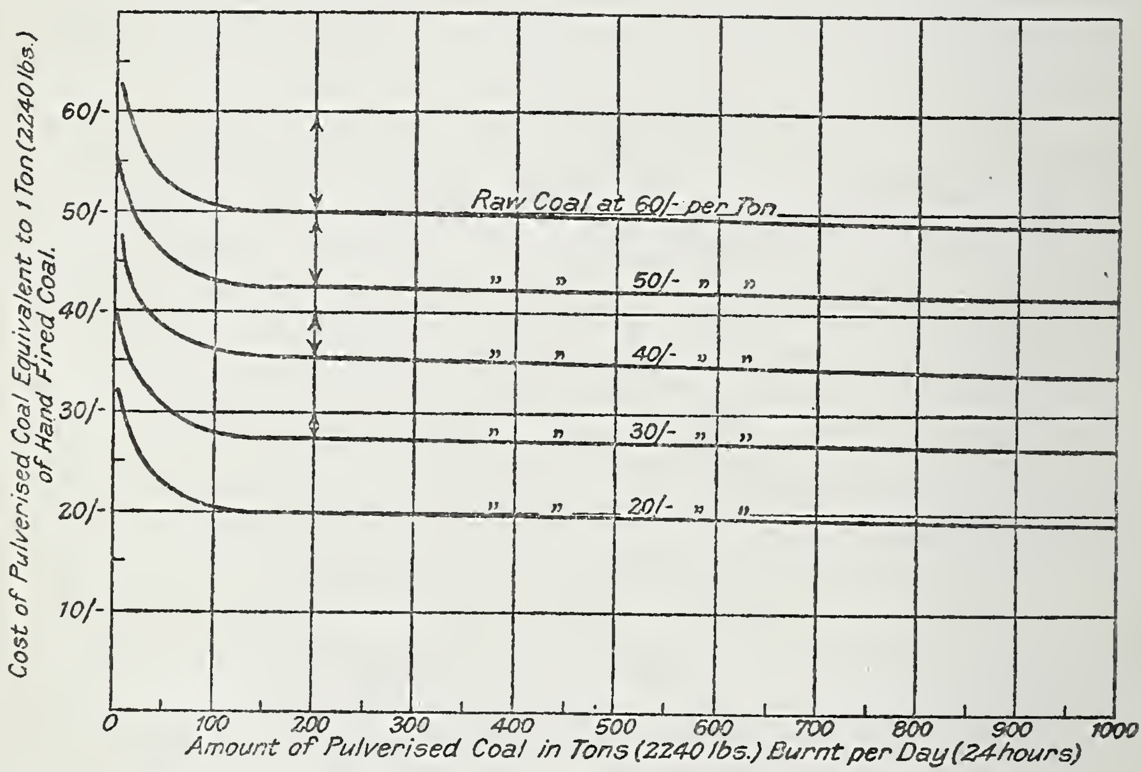

FIG. 51.—GRAPH SHOWING COST PER TON OF PULVERISED COAL for performing the same work as 1 ton (2240 lbs.) of hand fired coal, assuming a reduction of 25 per cent. by the use of pulverised coal and making allowance for all costs for preparation, etc., interest and depreciation on plant as set out in Table on page 141

Thus where 200 tons are burnt per 24 hours, the saving per ton of coal will be 10s., 7s. 6d., 4s. 9d., 2s. 3d., according as coal costs 60s.,

50s., 40s., or 30s. per ton. But if coal be 20s. per ton there will be no saving; and for a plant using only 50 tons per day there would at this price be a saving on the side of hand firing of about 3s. per ton.

In making these comparisons it must be remembered that there are indirect economies and other advantages which follow from the use of powdered fuel, which have been suggested in former chapters. These are not taken into consideration in these calculations.

The following Table from Harvey is of interest as showing the proportion of the total operating cost which is due to the different factors contributing to it:—

DETAILED COSTS FOR A PULVERISING PLANT OF 80 TONS' CAPACITY OPERATING AT 30 TO 35 TONS PER DAY (1918 VALUES)

1917–1918	Labour 6 to 7 men	Labour Insurance	Stores	Electric Repairs	Machining Repairs	Engineering Repairs	Electric Power	Total Operating Cost per ton
	s. d.	s. d.	s. d.	s. d.	s. d.	s. d.	s. d.	s. d.
October	3 9·65	0 0·5	0 10·9	0 9·5	0 6·95	...	0 9·85	6 10·85
Nov. .	3 4·4	0 0·5	0 10·6	0 9·25	0 11·8	...	0 11·4	6 11·45
Dec. .	3 5·75	0 0·5	0 10·4	0 10·35	0 4·3	0 0·9	0 11·0	6 6·7
Jan. .	2 9·0	0 0·5	0 4·15	0 6·9	0 3·2	0 0·95	1 1·65	5 2·35
Feb. .	3 5·7	0 0·5	0 4·15	0 5·9	1 1·55	0 1·9	0 11·2	6 6·4
March .	2 9·57	0 0·4	0 8·0	0 6·2	0 2·45	0 1·15	0 8·75	5 0·2

The average of these total costs over the six months works out to 6s. 2d. per ton of coal.

P. Frion, in a paper entitled "Le Chauffage au Charbon pulverisé," in *Chaleur et Industrie* for May, June and July 1921, discusses the question of cost of installation and operation, and illustrates it by figures for two plants, with daily outputs of about 50 and 500 tons of powdered fuel. He assumes the cost of installation to be 500,000 and 3,000,000 francs (1921), and the power needed for drying to be 4 and 2, for pulverising 30 and 12 kw. hours per ton respectively, and takes the coal needed in the drier to be 1·5 per cent., and supposes a loss through dust of another 5 per cent., of the coal dried.

The labour needed to deal with the coal, from its delivery at the works to its combustion at the burner, is taken as two men for the smaller and six for the larger installation. From these data he calculates the

following figures, assuming coal to be delivered at the works at the two prices of 100 fr. and 200 fr. per ton :—

	50 tons per day		500 tons per day	
Cost of coal delivered—per ton .	100·00	200·00	100·00	200·00
Interest and depreciation ,, .	5·55	5·55	3·34	3·34
Maintenance ,, .	1·73	1·73	1·04	1·04
Labour ,, .	3·12	3·12	0·94	0·94
Power ,, .	10·00	15·00	6·00	9·00
Coal used in drier ,, .	3·00	6·00	3·00	6·00
Total operating costs ,, .	23·40	31·40	11·32	20·32
Total cost of coal at burner ,, .	123·40	231·40	111·32	220·32

If, taking for example the smaller installation and the lower price for coal, we suppose that by another method, say hearth firing, coal can be brought upon the hearth at a cost of 112 fr. per ton, then obviously powdered fuel firing can only be economical if 112 tons of coal so fired can do the work of at least 123·4 tons fired by the other method, or if by the use of powdered fuel there is saved at least 11·4 out of every 123·4 tons, or 9·2 per cent., of the coal previously used.

A number of estimates of cost, both of installation and of operating, are available from American sources, chiefly dating from 1919. Although, owing both to the rapid changes in values and the changes in the rate of exchange during the last four years, the figures for costs have largely lost their significance, yet some of them are worth quoting because they show the relation between the installation or establishment costs and the cost of operating, and also because they give an indication of the relative cost per ton of coal in large and in small installations.

F. A. Scheffler and H. S. Barnhurst (American Society of Mechanical Engineers, June 1919) make the following estimates :—*Power.*—The power needed for crushing, drying and pulverising is from 12 to 13 kw. hours per ton. The power needed for transport and feeding varies very greatly with the size and nature of the installation, but may be put at 4 to 6 kw.

hours per ton, making the total power requirement 17 or 18 kw. hours per ton. The cost of power is estimated at 0·75 cent per kw. hour. *Repairs.*—The figure will naturally vary for different installations, but for material, labour and general upkeep for the whole equipment may be put at 7 to 10 cents per ton. *Drier Fuel.*—May be calculated at 1 to 1¼ per cent. of the coal dried. With an average moisture-content of 7 per cent. in the raw coal the cost will be 3 to 6 cents per ton, according to the cost of coal. *Labour.*—This, apart from other causes of variation, is very different in plants of different sizes. At 40 cents per hour the labour cost would be 14, 4 and 2½ cents per ton respectively in plants of 100, 1000 and 5000 tons' daily capacity. *Interest.*—The cost of a 100-ton plant is put at $64,000 and of a 1000-ton plant at $240,000. Interest at 6 per cent. on 365 days' continuous operation would be 10·5 and 3·9 cents per ton in the two plants respectively. *Depreciation.*—This is taken at 40 years' life on the building, 15 years' on the driers, and 20 years' on the rest of the equipment, and works out at 12 cents per ton on the 100-ton, and 4 cents per ton on the 1000-ton plant. *Taxes and Insurance.*—These are put at 3·5 and 1·3 cents per ton on the smaller and the larger plant respectively. These figures are summarised in the following Table :—

COST OF DELIVERING PULVERISED FUEL TO FURNACES

	100-ton Plant Dollars per ton	1000-ton Plant Dollars per ton
Power, 0·75 cent per kw. hr., 17 kw. hrs. per ton	0·1275	0·1275
Labour, 40 cents per hour	0·14	0·04
Drier coal at $5 per ton	0·06	0·06
Repairs	0·07	0·07
Total cost of operating	0·3975	0·2975
Interest at 6 per cent.	0·105	0·039
Depreciation	0·12	0·04
Taxes and insurances	0·035	0·013
Total cost of delivery	0·6575	0·3895

N. C. Harrison, in the same journal, gives as actual operating costs per ton at the Atlantic Steel Company's plant the following figures :—

	80 tons per day	90 tons per day	100 tons per day
	$	$	$
Power	0·22	0·195	0·176
Labour	0·19	0·19	0·19
Drier coal	0·134	0·134	0·134
Repairs	0·022	0·022	0·022
Total	0·566	0·541	0·522

Blizard, in his Canadian report, mentions several plants where the operating costs varied from 65 cents to as much as $3·05 per ton. In many of these plants the whole could have been remodelled and the cost considerably reduced. The engineer of one plant had plans for alterations which were calculated to bring the cost down from 103 and 125 to 85 cents per ton. Obviously, where powdered fuel firing is simply applied to an already existing plant, the cost is likely to be greater than where the whole plant has been designed for the purpose.

J. E. Muhlfeld, in a most valuable and instructive paper read before the Engineers' Society of Western Pennsylvania (*Proc.*, 1920, xxxvi. 243), gives the following detailed comparison of costs of powdered coal and of stoker firing for a large installation, the summary of which is :—

	Powdered Fuel	Stoker
	$	$
Total cost of preparation per ton prepared .	0·3325	0·009
Total cost of distribution per ton	0·0440	0·0494
Total cost of boiler firing per ton	0·5376	0·7933
Total cost of preparing, distributing and firing per ton	0·9141	0·8517

COMPARISON OF TOTAL OPERATING EXPENSE, POWDERED COAL *v.* STOKER FIRING, FOR 22,000 HORSE-POWER NOMINAL RATING BOILER PLANT IN COMBINATION WITH 45,000-KILOWATT CENTRAL POWER STATION

No.	Item	Powdered Coal	Stoker
	Summary		
1.	Total cost of coal per net ton, as fired (item 12+100)	\$3·7141	\$36·517
2.	Boiler h.p. hours developed per net ton of coal (2000 ÷ item 41) . . .	639	583
3.	Boiler h.p. hours developed per dollar expended for fuel and labour .	172	160
4.	Cost of firing per 100 boiler h.p. hours developed	58c.	61·5c.
5.	Cost of firing per boiler h.p. year (3000 hours)	\$17·40	\$18·75
6.	Cost of firing per kw. hour produced .	\$0·00286	\$0·00307
7.	Total cost of producing steam per year	\$1,710,847	\$1,888,126
8.	Net savings per year after deducting interest, depreciation, taxes, insurance and all operating and maintenance expenses	\$177,279	. .
9.	Extra investment required in order to effect saving in item 8	\$142,000	. .
	General Data		
10.	Kind of electric current available .	d.c. or. a.c.	d.c. or a.c.
11.	Cost of electric current per kw. hour .	0·75c.	0·75c.
12.	Cost of coal, per net ton, alongside .	\$2·80	\$2·80
13.	Water, per kw. hour, including auxiliaries	17 lbs.	17 lbs.
14.	Hourly rate and hours per day for firemen (24 hours at 45c.)	(3) \$32·40	(5) \$54·00
15.	Hourly rate and hours per day for assistant firemen (24 hours at 43.5c.) .	(3) \$31·22	(5) \$52·20
16.	Hourly rate and hours per day for ash handlers (10 hours at 42c.) . .	(2) \$8·40	(6) \$60·48

[*Continued*

No.	Item	Powdered Coal	Stoker
17.	Hourly rate and hours per day for millers (20 hours at 54c.)	(1) $10·80	..
18.	Hourly rate and hours per day for millers' helpers (20 hours at 43·5c.)	(3) $26·10	..
19.	Hourly rate and hours per day for conveyor attendant (20 hours at 45c.)	(1) $9·00	(1) $10·80
20.	Hourly rate and hours per day for inspector (24 hours at 54c.)	(1) $25·92	(2) $25·92
21.	Total labour per 24-hour day	$130·88	$203·40
	Coal Analysis, as fired		
22.	Run of mine	bituminous	bituminous
23.	Moisture	0·8	0·8
24.	Volatile matter	33·58	33·58
25.	Fixed Carbon	56·02	56·02
26.	Ash	9·6	9·6
27.	Sulphur	less than 1%	less than 1%
28.	B.Th.U.	13,380	13,380
29.	Number and kind of boilers	(14) B. & W.	(14) B. & W.
30.	Rated h.p. of each	1600	1600
31.	Total h.p. capacity of plant	22,400	22,400
32.	Hours per day operated	24	24
33.	Hours per day banked	6	6
34.	Days per year operated	365	365
35.	Average rating during operation	150	150
36.	H.p. hours operated per year	294,336,000	294,336,000
37.	Average B.Th.U. in fuel	13,380	13,380
38.	Average combined efficiency	80	73
39.	B.Th.U. utilised in boiler and superheater	10,704	9767·4
40.	Lbs. water evaporated from and at 212° per lb. of coal	11·03	10·065
41.	Lbs. coal per boiler h.p. hour	3·13	3·43
42.	Lbs. coal per hour during banked period	..	11,200
43.	Lbs. coal per day while operating	2,524,032	2,765,952
44.	Lbs. coal per day while banked 0·5 lb. per h.p. capacity per hour	..	67,200

No.	Item	Powdered Coal	Stoker
45.	Pounds coal per day, total for plant .	2,524,032	2,833,152
46.	Tons coal per year, total . . .	460,635·8	517,051·2
47.	Tons coal per hour in preparation plant (20 hours per day). . . .	66	..
	Installation Costs		
48.	Cost of preparation plant building, including foundation and bins .	$80,000	..
49.	Cost of preparation plant machinery and equipment	$220,000	$25,000
50.	Cost of distributing system machinery	$75,000	see item 58
51.	Cost of distributing system supports .	see item 58	
52.	Cost of boiler bins and supports .	see item 58	..
53.	Cost of boiler firing machinery and equipment	$240,000	$487,000
54.	Cost of boiler furnaces . . .	$84,000	see item 53
55.	Cost of boiler-room changes, when necessary	..	..
56.	Cost of ash-handling equipment .	$20,000	$65,000
57.	Cost of soot blower system . .	$10,000	$10,000
58.	Cost of boiler, installed . . .	$1,456,000	$1,456,000
59.	Total	$2,185,000	$2,043,000
	Operating Expense—Preparation Plant	$	$
60.	Total investment (item 48+49) . .	300,000	25,000
61.	Interest at 7% on item 60 . .	21,000	1750
62.	Depreciation at 5% on item 48 . .	4000	..
63.	Depreciation at 10% on item 49 .	22,000	2500
64.	Insurance and taxes at 2% on item 60	6000	500
65.	Total fixed charges on item 60 .	53,000	4750
66.	Total fixed charges on item 60, per ton prepared (item 65÷item 46) . .	0·115	0·009
67.	Cost of electric power per ton prepared	0·0975	..
68.	Cost of maintenance per ton prepared	0·0400	..
69.	Cost of lubricants per ton prepared, plus coal for drying . . .	0·05	..

[*Continued*

No.	Item	Powdered Coal $	Stoker $
70.	Cost of labour per ton prepared . .	0·03	..
71.	Total cost of preparation, per ton prepared	0·3325	0·009
	Operating Expense—Distributing System		
72.	Total investment (item 50+51) . .	75,000	see item 58
73.	Interest at 7% on item 72 . .	5250	..
74.	Depreciation at 5% on item 51 . .	..	..
75.	Depreciation at 10% on item 50 .	7500	..
76.	Insurance and taxes at 2% on item 72	1500	..
77.	Total fixed charges on item 72 . .	14,250	..
78.	Total fixed charges on item 72 per ton handled (item 77 ÷ item 46) . .	0·031	..
79.	Cost of electric power per ton handled	0·0015	0·0008
80.	Cost of maintenance per ton handled .	0·0025	0·04
81.	Cost of lubricants per ton handled .	0·002	0·001
82.	Cost of labour per ton handled . .	0·007	0·0076
83.	Total cost of handling in distributing system, per ton	0·0440	0·0494
	Operating Expense—Boiler Equipment		
84.	Total investment (items 52, 53, 54, 55, 56, 57 and 58)	1,810,000	2,018,000
85.	Interest at 7% on item 84 . .	126,700	141,260
86.	Depreciation at 5% on item 52 . .	..	..
87.	Depreciation at 10% on item 53 .	24,000	48,700
88.	Depreciation of furnaces . . .	see item 97	see item 97
89.	Depreciation at 10% on item 56 .	2000	6500
90.	Depreciation at 10% on item 57 .	1000	1000
91.	Taxes and insurance at 2% on items 52, 53, 55, 56, 57, and 58 . . .	34,520	40,360
92.	Total fixed charges on item 84 . .	188,220	237,820
93.	Total fixed charges on item 84 per ton fired (item 92 ÷ item 46) . . .	0·40	0·46
94.	Cost of electric power per ton fired .	0·015	0·069
95.	Cost of maintenance per ton fired .	0·02	0·14

No.	Item	Powdered Coal $	Stoker $
96.	Cost of lubricants per ton fired . .	0·002	0·001
97.	Cost of furnace repairs per ton fired .	0·04	0·03
98.	Cost of labour, including ash handling, per ton fired	0·0606	0·0933
99.	Total cost of boiler firing, per ton fired	0·5376	0·7933
	Operating Expense—Total		
100.	Total cost of preparing, distributing, and firing coal per net ton (items 71, 83 and 99)	0·9141	0·8517

It is to be remarked that while the cost of fuel, as compared with the period before the war, has very greatly increased, interest rates have not increased in the same ratio, so that installation and fixed charge costs, then prohibitive, now bear a smaller ratio to the whole operating cost, and may be undertaken with greater certainty of being made remunerative through the saving which powdered fuel can effect in actual work.

The following figures are taken from a tender from the Powdered Fuel Plant Company for a plant for firing two Stirling boilers, each having a nominal evaporation of 20,000 lbs. per hour:—

There will be a C.R. 4 turbo-pulveriser for each boiler, with hopper having a capacity of 3000 lbs. of coal per hour at 1450 r.p.m.; each will be connected to a 60 h.p. motor (the normal power needed is about 50 h.p.). There will be two burners to each boiler, of substantial construction in cast iron, with adjustable nozzles.

Piping of mild steel welded, with flanged connexions, air- and dust-tight. Breeches pieces of cast iron, with deflector valves to control fuel supply to each burner. Isolating valves fitted where shown. A Venturi mixer would be inserted in the pipe-line.

Two pipe-ventilated motors suitable for 3-phase 50 cycles 500 volts circuit, capable each of developing 60 h.p. at 1445 r.p.m. Suitable starter and two flexible couplings between motors and turbo-pulverisers.

The pulverising, transporting and burning equipment as above is quoted at £1450, and the electrical equipment at £375: total, £1825.

The cost of replacing wearing parts, based on 50 weeks' work in the year, of 126 hours per week, is estimated at £40 per annum: the beater blades, £5 per set, needing replacement every six months, the liners, £20 per set, every 14 months, and the primary air and powdered coal fan, £24, after about $2\frac{1}{2}$ years.

Taking electric current at 1d. per unit, the cost of pulverising and burning a ton of fuel is put at 2s. 8d. to 2s. 10d., according to the coal.

H. D. Savage, in his paper at the American Iron and Steel Institute, makes the following comparison of operating costs between powdered coal and stoker fired boilers:—

COMPARATIVE OPERATING COSTS

"The cost of fuel preparation is another point that the critics of powdered fuel burning have been prone to emphasise. It may be stated that the cost of firing coal, from coal car to ash car, is not greater in a pulverised coal plant than in a modern stoker plant. This statement, being so widely at variance with the generally accepted understanding of the situation, must be very carefully analysed. This conclusion is based on the following calculation, and is made on the basis that the extra steps necessary for the preparation of coal for firing in pulverised form as against the firing of coal on either Type E or Multiple Retort Stokers is offset by the cost of driving the stoker and blower auxiliaries in these latter plants.

"It may be assumed that the power required to operate the forced draft fans for underfeed stokers and the power required for driving the stokers will be between 3 and 5 per cent. The stoker company will say that this is true, but that the net charge for power required to operate the stokers and deliver the air will not be more than 20 per cent. of this figure, for the reason that the exhaust steam from the engines or turbines used for driving the fans and stokers is returned to the feed water, making the net charge for this power 1 per cent. or less.

"We have considered a plant with twenty 600 h.p. boilers and underfeed stokers of the type E or Multiple Retort Type, and the steam required for operating the stokers and forced draft equipment, when developing 20,000 boiler h.p., is given in Table on page 153.

"We also show figures giving the total steam for operating the motors required in such a plant to supply the power for the drier, pulverising equipment, distributing equipment and feeding and burning equipment, with a pulverised fuel system replacing the underfeed stoker.

COMPARISON OF POWER CONSUMPTION FOR PULVERISED COAL PREPARATION AND FIRING EQUIPMENT AS AGAINST STOKER AND AUXILIARY EQUIPMENT.

Comparison based on an assumed boiler plant, consisting of twenty 600 h.p. boilers operated at 1000 h.p., giving a total of 20,000 h.p.

Type E Stoker

Forced draft requirements, 300,000 cubic feet at $5\frac{1}{2}$ inches water pressure =450 h.p.		
450 h.p. by 40 lbs. of steam per brake h.p.	18,000	lbs. steam per hour
Stoker drive at 1% steam generated . .	6,900	,, ,,
Total power required	24,900	,, ,,

Multiple Retort Stoker

Forced draft requirements, 300,000 cubic feet at $5\frac{1}{2}$ inches water pressure =450 h.p.		
450 by 40 lbs. of steam per brake h.p. .	18,000	lbs. steam per hour
Stoker drive at 140, retorts at 1 h.p. at 50 lbs.	7,000	,, ,,
Total power required	25,000	,, ,,

Pulverised Coal

Drier—based on 42 lbs. water rate per kw.	21	lbs. steam per ton of coal
Pulverising—based on 42 lbs. water rate per kw.	688	,, ,, ,,
Distributing—based on 42 lbs. water rate per kw.	17	,, ,, ,,
Feeding and burning—based on 42 lbs. water rate per kw.	94	,, ,, ,,
Total power per ton	810	,, ,, ,,

20,000 h.p. at 80% efficiency with 13,500 B.Th.U. = 3·1 lbs. per b.h.p. = 31 tons per hour.

31 tons by 810 lbs. steam per ton = 25,110 lbs. steam per hour with driers.

31 tons by 790 lbs. steam per ton = 24,500 lbs. steam per hour without driers.

Summary

Power required of auxiliary equipment in lbs. of steam per hour:

Type E Stoker	Multiple Retort Stoker	Pulverised Coal with Drier	Pulverised Coal without Drier
24,900	25,000	25,110	24,500

"We have not considered the coal used for the drier, for the reason that if the moisture is taken out in the drier it is not necessary to do it in the furnace, as would be the case if no drier were used, or if the coal were being burned on underfeed stokers.

"This plant operating at 20,000 h.p. burns 31 tons of coal per hour, and the power required for preparing the coal is slightly less than 20 kw. per ton. This figure is based on actual operation.

"It has become the practice among engineers to estimate the power required for preparing the fuel at about 20 kw. per ton and making this a net charge. Therefore, if their cost per kw. was $1\frac{1}{2}$ cents they would figure a charge of 30 cents per ton for preparing the fuel.

"The point we wish to make is that this preparation cost should be considered in the same manner as the cost of power for operating the fans and stokers, in order to have the two systems on a comparable basis. We have made our estimates with the idea of using in this plant a non-condensing turbo-generator of approximately 750 kw. capacity. This is to supply power for the pulverised fuel system. This machine would operate with high-pressure steam and exhaust at atmospheric pressure into the feed water heating system, the same as would be the case with the auxiliaries operating the stoker equipment. The steam consumed by this turbo-generator would be not more than 42 lbs. per kw., and on this basis the amount of steam required for preparing the fuel would be approxim-

ately the same as the steam required for operating the stoker equipment. Therefore, if the power required for operating the stoker equipment is considered as less than 1 per cent. (taking into account the heat returned to the feed water), the power required for preparing the fuel in the pulverised fuel plant is the same, and instead of 30 cents per ton, is less than 6 cents per ton, if the total cost per kw. is taken as $1\frac{1}{2}$ cents.

"It is interesting to note that the steam required for operating the pulverising equipment in this plant would increase the temperature of the feed water approximately 36 degrees. There are very few large central stations in which this steam could not be used in the feed water. If economisers were used, it might be advisable to take the power for operating the motors in the pulverised fuel plant direct from the main turbo-generator, but the point we wish to make is that the same condition would exist if underfeed stokers were used, and that the net charge for power for either system is the same.

"We believe that it is generally agreed that good stoker practice on continuous operation using Eastern coals will show approximately 70 per cent. efficiency. With a correctly designed and properly operated pulverised fuel system, we believe that it is fair to assume that it can be operated continuously at 10 per cent. higher efficiency than this—namely, 77 per cent.

"This conclusion is based on the results obtained on tests at the Milwaukee Electric Railway & Light Company's plant, and operating results at Oneida Street station, Morris & Co. plant and St Joseph Lead Co. plant.

"Assuming that the plant considered above, operating on a 50 per cent. load factor, will burn with stokers 400 tons per day and with a pulverised fuel system 360 tons, with \$8 coal this would represent a saving of \$116,800 per year, against which there would be charged interest and depreciation on additional cost of the pulverised fuel plant, which at the outside would not be over \$16,000, making a net saving of \$100,000 per year.

"In confirmation of this comparison, it was found recently, in making figures covering the change from stoker to powdered coal in a plant having four 1240 h.p. boilers, that the forced blast fans for each boiler required 60 h.p. when the boilers were operated at 300 per cent. of rating, whereas

50 h.p. per boiler would prepare and furnish the necessary coal for 300 per cent. of rating."

The following estimate of cost of equipment and power required for working was recently made by the Fuller Company :—

Pulverised coal equipment required for boiler plant fitted with 4 boilers, each capable of evaporating 13,000 lbs. of water per hour from and at 212° F. Coal used $\frac{3}{4}$-inch smalls, containing 16 per cent. volatile, 25 per cent. ash, 4 per cent. moisture. Thermal value, 12,500 B.Th.U.'s per lb. Load maintained 24 hours per day, 7 days per week.

1 No. 3 Fuller mill, with motor, storage bin, over-mill, elevator for raising crushed coal to bin, and transport system for transporting pulverised coal through 100-feet pipe to bunkers, serving boilers.

Boiler firing equipment consisting of 4 pulverised coal bunkers, with feeders and burners for 4 boilers, air supply fans, motors, and pipes to connect fans, feeders and burners.

Total cost, £3542.

Space required by milling equipment, 12 feet by 28 feet.
Guaranteed sustained efficiency, 83 per cent.
Fuel required by 4 boilers per hour, 4864 lbs.
Fuel required by 4 boilers per 24 hours, 116,736 lbs.

Power required by Milling Equipment and Transport of Pulverised Coal to Boilers, say 100 *feet distant*

1 No. 3 mill, operating $14\frac{1}{2}$ hours at 50 h.p. . .	=725	h.p. hours
1 Pulverised coal pump, operating $14\frac{1}{2}$ hours at 8 h.p.	=116	,, ,,
	841	,, ,,

Tons coal used $=\frac{116,736}{2204}=52{\cdot}96$ metric tons in 24 hours.

Power per ton$=\frac{841}{52{\cdot}96}=15{\cdot}88$ h.p. hours per ton.

Power required at Boilers

4 Feeders, operating 24 hours at $\frac{1}{2}$ h.p. each . .	= 48	h.p. hours
1 Air supply fan, operating 24 hours at 15 h.p. . .	=360	,, ,,
	408	,, ,,

Summary—Motor H.P. Hours

Power required by milling plant . . 841 h.p. hours
Power required by feeders at boilers . . 408 ,, ,,
Total power required by Fuller system=1249 h.p. hours per day, or 23·57 h.p. hours per ton of coal.

The following figures, furnished by Messrs Edgar Allen & Co., afford an approximate comparison of working costs of the reheating furnace in their works, when worked by hand firing and by powdered fuel; the labour of spreading the coal to dry for the pulveriser is set against that for the firing of the hand-fired furnace, as mentioned in the description of the furnace, p. 105. The first column of figures refers to a period of four months of intermittent work, and the second to a continuous period of a week:—

	Solid Fuel	Powdered Fuel
Turns worked . .	$65\frac{3}{4}$	$65\frac{3}{4}$
Steel heated . . .	104 tons	163 tons
Slack or coal used . .	71 ,,	64 ,,
Slack per ton of steel .	13·75 cwts.	7·85 cwts.
Cost of fuel . . .	£126, 2s.	£55, 15s. 7d.
Cost of motor . .	..	£32, 17s. 6d.
Cost of wages . .	..	£19, 4s.
Total cost per ton of steel	£1, 15s. 6d.	13s. 3d.
Turns worked . .	6	6
Steel heated . . .	9 tons, 9 cwts.	16 tons, 10 cwts., 3 qrs.
Fuel used . . .	7 tons	5 tons, 12 cwts., 2 qrs.
Fuel per ton of steel .	14·8 cwts.	6·8 cwts.
Cost of fuel . . .	£13	£5, 4s.
Cost of motor . .	..	£2, 12s.
Cost of wages . .	...	£1, 6s. 3d.
Total cost per ton of steel	£1, 7s.	11s. 1d.

ADVANTAGES

In comparing powdered fuel firing with the ordinary grate firing of lump coal there are many reasons for giving powdered fuel preference.

First of all, complete combustion is much more easy to secure. In

the ordinary method of burning on a hearth the coal is disposed in layers, and the air can only come into contact with it partially and gradually, through the furnace bars and at the upper surface. The upper coal is carbonised by the hot lower coal, and special arrangements have to be made for the supply of air to burn the gases which are evolved during this carbonisation. It is impossible to secure complete combustion without a considerable excess of air, even with mechanical stokers, and many boilers are worked regularly with a carbon dioxide content in the flue gases of not more than 12 per cent. With powdered fuel, on the other hand, combustion can be made complete with very little more than the theoretically needed quantity of air, so that the highest possible temperature of combustion may be realised, and the least possible loss of heat from the installation, due to escape of the products of combustion at a temperature above that of the air, will occur. In cement furnaces work can be carried on and complete combustion assured with not more than 1 per cent. of excess air, and this should be possible with other furnaces—indeed the only reason for admitting excess air with powdered fuel is the necessity in some cases of protecting the refractory materials of the furnace from too high a temperature.

In the ordinary use of fuel there is not only the difficulty of ensuring the complete combustion of the volatile matters from the coal and avoiding the loss and nuisance arising from smoke, but the solid combustible material is never completely burnt out, and there is always a certain amount of unburnt carbon among the ashes. The amount of this varies of course with the particular plant in use and with the nature and quality of the coal; but in nearly all cases it reaches at least 10 per cent. of the ash, which for a coal containing 15 per cent. of ash means a loss of 1·5 per cent. or more of the total carbon in the coal. In gas producers an average value of 2·5 per cent. would probably not be too high. With powdered fuel, on the other hand, the loss from this cause diminishes to an almost negligible quantity. In tests made at the Oneida Street power station (see p. 122) the loss on this account varied in different trials from 0·8 down to 0·3 per cent. of the total coal fired. The coals contained from 10 to 14 per cent. of ash.

Another advantage of powdered fuel is the easier regulation and more complete control that it permits. The speed of entry of the fuel, and the proportions of fuel and of primary and secondary air can be varied readily, so as to obtain the best conditions of combustion and utilise to the best advantage the heat evolved, according as a long and gentle, or a short and intensely hot flame is desired. In powdered fuel firing, if the right amounts and proportions of coal and air are once established, they continue without any effort on the part of the stoker, whilst with hearth firing accidental irregularities in the hearth covering alter them at once. This difference is even more marked at partial load than at full load. When adjustment is needed the burners or the fuel feed can be adjusted by a turn or two of the hand; but every displacement of the mechanism of the stoker or of the coal on the hearth affects the equilibrium of a large mass of coal, and the new equilibrium is not established for some considerable time. Skilled and careful stoking can compensate for this to a great extent; but one man can deal with only a very limited number of boilers. The easy adjustment of the proportions of powdered coal and air, too, permits of the attainment and the continuance of any desired quality of flame, whether oxidising or reducing.

A third advantage is the readiness of the installation for work. Lighting or relighting is quick, and the firing can be pushed to full power more rapidly than with hearth firing. The limitation to the rate at which steam can be got up is chiefly due to consideration for the brickwork of the combustion chamber.

Loadless losses are also less with powdered fuel than with hearth firing. The entry of air and its passage by the boiler flues to the chimney can be more easily prevented, and thus the loss of heat from the boiler lessened. No fuel is used during "banking-up," and full fire is almost instantaneously ready on restarting. In regard to loadless periods, Savage says of a large plant that "The flexibility of powdered coal firing makes it readily responsive to widely fluctuating demands, and no small amount of saving occurs during the banked periods." A record of a banked period at the Oneida Street station on 19th August 1919 shows that the fuel feed was shut off, the uptake damper and the auxiliary air inlets were closed at

9 P.M., and the boiler outlet to header closed at 9.20 P.M. There was then 175 lbs. pressure on the boiler. During the next $2\frac{1}{2}$ hours the safety valves were released for intervals of about 1 minute 15 times; and at 7 A.M., when the fuel feed was started again and the boiler outlet to header opened, there was still 155 lbs. pressure: a drop of only 20 lbs. During these periods no coal is fired, and there is no flow of air through the furnace. The furnace brickwork acts as a regenerating medium, so that loss of pressure is exceedingly slow, and the boiler can be brought back on the line in about four minutes after the fuel feed is started.

But the flexibility of powdered fuel firing is of advantage not only because of the possibility of rapid starting and the diminished losses during periods of no load, but also during work. The efficiency of the burners, though it varies, varies less at partial load than that of grate firing; and as the capacity of the burners to supply heat is usually greater than the receptive and evaporative capacity of the boiler (whereas with hearth firing the capacity of the boiler is usually limited by that of the hearth to supply heat), they can be worked to take peak loads: this, too, with very little loss of efficiency.

In furnace work the possibility of controlling the character of the atmosphere is of very great importance, and in this respect powdered fuel has very great advantages. The supplies of coal and of air are so easily regulated independently of one another that an oxidising or a reducing atmosphere may be obtained and maintained at will, and, where it may be necessary, a change in the nature of the atmosphere can be effected with great rapidity.

Münziger computes that a boiler working with powdered fuel has an advantage, over one with hearth firing, of from 2 to 14 per cent. on the coal bill, according as the daily working varies from 24 hours down to 6; but he would add to this at least 4 per cent. for the advantages which powdered fuel possesses in being better able to deal with fuels high in ash, or with variations in the quality of the fuel, and on account of its being less subject or sensitive to the idiosyncrasies of workmen. Thus an installation whose daily work is not more than corresponds to 9 to 12 hours

at 80 per cent. of fuel load will save about 10 per cent. by working on powdered fuel.

Frion, in summary, concludes that powdered fuel working increases the output of boilers by 4·5 to 11·5 per cent., without economisers, and by 3·5 to 6·5 per cent. where economisers are used. It increases that of furnaces by 5·5 to 13·5 per cent., but the possibilities of more economical utilisation of the flame when powdered fuel is used may increase this advantage sometimes to as much as 30 per cent.

The efficiencies of oil and of powdered fuel are very similar; the advantage of powdered fuel over oil lies in its lower cost. In other respects, oil has the advantage: there is no need for elaborate plant for its preparation, it has a much higher calorific value, whether equal weights or equal volumes be considered, it can be burned in much smaller space, and there is no ash to be dealt with.

Powdered fuel avoids the losses of gasification, never less than 20 per cent., and often much more, especially if producers are not fed with the particular fuel for which they are adapted. Producers cannot work economically with fuels very high in ash, which can be burnt quite economically in the powdered form.

Since the combustion with producers takes place in two stages, the final stage cannot produce the temperature attainable by powdered fuel, where the whole heat of combustion is available at one stage (see p. 21). Any tars and similar products which may be recovered from the producer process are of course lost from the whole calorific value of the fuel.

J. E. Muhlfeld (*Proc. Eng. Soc. of W. Pennsylvania*, 1920, xxxvi. 243) makes the following comparisons of the cost of energy from powdered coal, producer gas and fuel oil, assuming coal of 12,000 B.Th.U. per lb. to cost \$4·95 per ton (5·50 pulverised at furnace burner, 6·00 put through producer), fuel oil of 138,700 B.Th.U. per gallon to cost \$0·09 per gallon, and a 78 per cent. producer efficiency. The number of B.Th.U. obtained for 1 cent would be 43,636, 31,200, 15,411 respectively; so that powdered coal at \$15·56 per ton, or coal for producer gas at \$10 per ton, would be equivalent to oil at \$0·09 per gallon, and powdered coal at \$7·65 per ton would be equivalent to coal for producer gas at \$4·95 per ton.

A very important advantage which powdered fuel possesses is one which has been already indicated—namely, the possibility of burning, completely and efficiently, inferior fuels, especially those containing high percentages of ash. Even at present installations are in regular work burning fuel which on account of its high ash-content could not be successfully burnt on grates; and the possibilities of using such fuels in the future, especially at and in the neighbourhood of collieries, where transport charges are low, present a prospective economy of very great importance, making available as they do large amounts of coal which it is now not worth while to bring to the surface.

The reduction in the amount of hand labour, some of it labour of a very arduous kind, which the substitution of powdered fuel for grate firing permits, is another feature which ought to be kept in mind. Muhlfeld, in a paper already quoted, mentions an instance in which two continuous billet-heating furnaces were converted from hand firing to powdered fuel firing, with the result that not only was the fuel consumption per ton of metal heated reduced from 450 to 160 lbs. of coal, but the total number of workmen over the 24-hour period was reduced from 36 to 7. Though reduction in this ratio may not always be possible—it will vary with the size, the nature and the circumstances of the installation—yet in all cases a considerable reduction will be effected.

The disadvantages urged against powdered fuel are the difficulties of dealing with the ash, the troubles with refractory materials, the cost of installation and upkeep of the plant, and the danger from fires and explosions. All of these save the last have been discussed in earlier parts of this book; and it has been indicated that most of the troubles with ash and with refractory materials have been overcome as longer experience has suggested methods of dealing with them. The question of fires and explosions is one which deserves treatment in some detail.

Not only is coal-dust a combustible substance, which will burn when brought into contact with air under appropriate conditions; but, being so finely divided, and each particle being, when the mass is mixed uniformly with the necessary quantity of air, in such immediate proximity to the air which it needs, and also to the neighbouring particles of coal,

the mixture is explosive—that is to say, if ignition occurs at any place in the mixture it can be transmitted from particle to particle at a very high speed, so that the energy of combustion of the whole mass is developed almost instantaneously, with corresponding effects. Such a mixture behaves in many respects almost identically with a mixture of a combustible gas and air in the right proportions for complete combustion ; and experience in coal mines has shown that the explosion of coal-dust and air is a thing to be dreaded and to be provided against, equally with the explosion of fire-damp and air.

There is indeed one respect in which mixtures of coal-dust and air are more dangerous than those of gas and air. The most violent explosion of a gaseous mixture of course occurs when the gas and air are present in the exact proportions required for their reaction ; and if such a mixture be diluted with increasing proportions of either gas or air the violence of the explosion decreases, until a mixture is reached in which it is not propagated at all. The diluting gas increases the volume to such an extent, and separates so far from one another the reacting particles, that the propagation of inflammation from particle to particle is seriously interfered with, and the whole operation is slowed down. But the actual volume of the coal in an explosive mixture of coal-dust and air is so small that a further addition of coal-dust makes very little difference in this respect ; and although during the explosion the additional coal-dust may be heated up and partly carbonised with evolution of gases of considerable volume, yet the explosibility of the mixture is not diminished in the same way as that of a gaseous mixture would be by a corresponding extra quantity of the combustible gas. It is not, therefore, safe to assume that a mixture with a certain excess of coal-dust will not explode, from a knowledge of the behaviour of explosive gaseous mixtures.

The amount of air which a given quantity of coal will need for complete combustion depends, naturally, on the composition of the coal. An ordinary bituminous coal containing, say, 85 per cent. of carbon and 5 per cent. of hydrogen will require about 11 times its weight of air, so that 1 lb. will need about 140 cubic feet, or a cubic inch about 7 cubic feet. The explosibility of a mixture of coal and air in these proportions will not be

seriously diminished by the addition of a considerably greater amount of coal-dust; and in tests by the American Bureau of Mines it was found that a mixture containing little more than one-fourth of this amount of coal-dust was still explosive.

It is not strange, then, that the danger of fire or explosion in powdered fuel plants has been urged as an argument against the introduction of the system; and the actual occurrence, in the early days of its application, of fires and explosions, sometimes with fatal results, has added strength to that argument. Impartial investigation into these occurrences has shown, however, that their causes were such as might easily have been avoided, and that with the exercise of proper and reasonable care powdered fuel firing is as safe as any other method of using fuel.

Mr L. D. Tracy, on behalf of the American Bureau of Mines, investigated this matter very thoroughly, and published a very full report in a paper read before the Engineers' Society of Western Pennsylvania (see their *Proceedings*, 1921, xxxvii. 259). For much of what follows, the author is indebted to this very comprehensive report.

Fires have occurred in various parts of powdered fuel installations. In some cases the cause of the ignition of the coal has been obvious; in other cases there has been no discoverable cause, and it has been attributed to "spontaneous combustion." Even at the ordinary temperature, coal very slowly oxidises when in contact with air, and the rate at which this oxidation occurs rises rapidly with the temperature. In the ordinary analytical operation of determining the amount of moisture in a sample of coal, which consists in heating a weighed quantity of the coal at a temperature just over the boiling-point of water, and reweighing it from time to time until it ceases to lose weight, when the total loss of weight is taken to be the weight of moisture in the portion taken, there frequently comes a time when, instead of losing weight, the coal actually gains; and this gain is found to be caused by the coal absorbing oxygen from the air. The more finely the coal is powdered, and the greater, therefore, the surface it exposes, the more rapidly will this absorption of oxygen occur; and as it is a process which is accompanied by the evolution of heat, if the coal be so circumstanced that this heat is not carried away as rapidly as it is

produced, the temperature will gradually rise, and may rise to such a point that ignition will take place. This is the explanation of cases of so-called "spontaneous combustion"; and to avoid the likelihood of their occurrence it is necessary to avoid the conditions under which they are likely to arise—that is to say, the storage for long periods of large quantities of coal, especially in a finely divided state, and at high temperatures.

In installations in which coal is dried the coal should leave the drier at temperatures considerably below the boiling-point of water. In the mill this warm coal is powdered finely, and may possibly get into the circulating system still at a fairly high temperature. The experiments quoted under the head of Pulverising (p. 64) show that the temperature does not ordinarily rise, and with warm coals falls, during the process of grinding; and the introduction of air for the transport of the finished ground coal will still further reduce the temperature (coal leaving a Raymond pulveriser at 160°-180° F. will reach the storage bin at 140°-160°, and at the consuming bin its temperature will have fallen to 80°); so that in normal circumstances the conditions for spontaneous combustion are not likely to arise here. The time during which a given quantity of coal will remain in the storage bin is not usually great, as the coal is used up so rapidly when the installation is at work; so that if care be taken to have the storage bins in places where they are not likely to get heated from the outside, little fear of spontaneous combustion need be entertained here either. Abnormal circumstances are to be guarded against: the accidental introduction of overheated coal into the pulverising plant; long storage of the powdered coal, through accidental stoppages or other interruptions of the working of the installation.

Fires have undoubtedly occurred through the introduction of overheated coal into the system, whether from overfiring the drier or from stopping the drier whilst the fire was maintained, so that the contained coal was exposed to the high temperature for a much longer time than normally.

In plants using the circulating system, fires have sometimes occurred by lighting back from the burners. If the air pressure in the fuel feed pipes should drop below that of the secondary air, whether from stoppage of the fan or from obstruction, the secondary air may blow back into the

fuel feed circuit, carrying sparks or hot gases from the burner mouth, which may set the mixture in the fuel feed system on fire. The same thing may possibly occur through obstruction at the burner mouth, from deposition of carbon through defective burning. In this case it is not the drop of pressure in the fuel feed, but the rise of pressure of the secondary air caused by the obstruction, that may drive the air, and hot gases or sparks accompanying it, back into the fuel feed. The remedy against such a possibility is of course the regular examination of the burners to see that no choking occurs.

If a fire does occur, whether in a storage bin or in a transport pipe, the amount of air present will as a rule be not nearly sufficient for the combustion of the coal; and unless in some way communication is established with the outside air, the coal will merely smoulder and partially carbonise the neighbouring coal. Unless this carbonisation causes the coal to stick together, so that it will not flow, it may be possible to feed the heated coal through the burners until the bin or transport pipe is emptied.

We saw that a cubic inch of coal needed about 7 cubic feet, or more than 12,000 times its volume of air, for complete combustion, and hence the powdered coal in a bin, associated (p. 67) with one to two times its volume of air, has only from $\frac{1}{12,000}$th to $\frac{1}{16,000}$th of the amount it needs. In the powdered coal main in the Holbeck system there is much more air —nearly half of that needed for complete combustion—and a fire started there would be able to carry itself on, although the carbon dioxide generated by the combustion would soon choke the fire, and the coal would smoulder rather than burn.

In the process of emptying, however, towards the end, the proportion of air, whether in bin or transport line, increases; and before starting up again (for in beginning, as at the end, the air is for the time in excess) it is imperative to make sure that no burning or smouldering coal remains, but that all is thoroughly cleaned out.

The presence of dust in the atmosphere of a powdered fuel plant is to be avoided, as far as that is possible. Perfect tightness of all joints and, wherever possible, a slight vacuum rather than excess pressure internally are to be aimed at. Dust in the atmosphere settles on every available

place or object, and is ready to fill the atmosphere again whenever it may be disturbed. Tracy gives a number of analyses of dust from girders, pipe-lines, and furnaces, and from the floor around furnaces, in installations using powdered coal :

Material	Volatile Matter	Fixed Carbon	Ash	Ratio of Volatile Matter to total Combustibles
Pure coal . .	36·81	52·84	9·28	0·42
Mill dust . .	23·54	51·24	24·36	0·31
„ . .	20·61	50·88	27·43	0·28
„ . .	15·91	53·26	29·76	0·23
„ . .	10·99	56·29	31·83	0·16
„ . .	7·17	63·68	27·78	0·10
Floor dust .	25·66	33·07	40·48	0·43
„ . .	33·98	36·59	28·25	0·48

Investigations of the Bureau of Mines on the explosibility of coal-dusts have shown that it depends on the ratio of the volatile to the total combustible matter, and that for any given value of this ratio the dust must contain a certain minimum proportion of inert matter before it will be rendered non-explosive. This minimum proportion is for the second of these samples 68 per cent., and for the last two about 78 per cent. ; thus the second one is short by about 44 per cent., the last but one by 38 per cent., and the last by 50 per cent. of the amount of inert matter that would be needed to make them non-explosive. In other words, all of these three dusts are explosive, and the same precautions are needed to prevent them from mixing with air and thus causing the risk of an explosion that would be needed if they were pure coal-dust.

Explosions are recorded, both by Tracy and by others, in which pulverised coal was being delivered by high-pressure air to a storage bin, and the air-tight lid of the bin was opened before the delivery had ceased and the pressure had been released. The air blew out a cloud of dust which ignited at a flame near by and exploded. In one of these instances the storage bin was directly over the furnace which it fed.[1] In such

[1] In another, the delivery to a bin, also near a furnace, was not stopped in time, so that the bin overflowed, and the cloud of dust fired at some hot slag.

installations it would seem advisable to have the bins so placed that direct communication with the furnace in this way would not be possible. In one installation mentioned by Tracy the bins are outside the wall of the building; and though they are unprotected no trouble through condensation of moisture in the coal during cold weather has occurred.

In air-transport systems the weak spot mechanically is the fan. An explosion is quoted which occurred in a bolt and rivet manufactory which almost certainly started in the fuel feed circuit, probably through a back draught from the furnace. The feed pipe was strong enough to stand the force of the explosion, which, however, burst the fan when it reached it. Tracy suggests the desirability of having a branch pipe near the fan with a release-door, in case of an explosion.

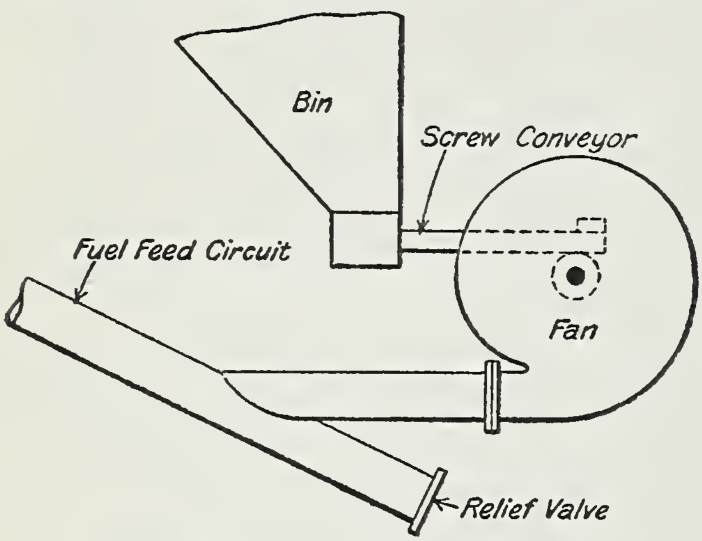

Fig. 52.—Explosion "Safety-Valve"

The sketch, Fig. 52, indicates the arrangement. The relief-door is placed at the end of a straight continuation backwards of the fuel feed line into which the delivery pipe from the fan comes at an obtuse angle.

The following series of recommendations, from Tracy's paper, admirably summarises the whole question of the danger of explosion in powdered fuel plants :—

There should be absolute cleanliness, and freedom from any accumaations of dust, both in the pulverising plant and in the buildings in which the pulverised coal is being used as fuel.

Accumulations of dust on the floor or machinery should never be brushed or swept up without either wetting the dust or thoroughly mixing with an excess mixture of fine incombustible material.

All coal pulverising plants should be adequately ventilated and lighted

and, when practicable, some method of cleaning by vacuum systems should be installed.

All open lights in and around coal pulverising plants should be prohibited, and employees should not be allowed to smoke while in the building. This rule should apply to superintendents and other officials who casually visit the plant, as well as to the regular attendants.

The drier and drier furnace should be separated by a fireproof partition from the pulverising mills, conveying machinery and storage bins.

Where the furnaces or boilers are equipped with individual fuel bins, these bins, if possible, should be isolated from the boilers or furnaces.

All pulverised coal bins should be tightly closed and never opened if there is any possibility of ignition from an open flame. Bins should be equipped with automatic indicators to indicate the amount of coal in the bin.

Only men of known reliability should be entrusted with the direct operation of a drier. It may be more economical in the long run to pay a higher wage to a good man than a smaller wage to an unreliable man or boy.

Especial care should be taken in order not to overheat the coal in the drier, and recording pyrometers should be installed to enable the officials of the plant to check the operation of the drier.

The operation of the drier should never be stopped while it contains a charge of coal.

Fire in the drier furnace should never be started with paper, shavings or any light combustible material.

Because of the liability of spontaneous combustion fine coal at a temperature over 150° F. should never be stored in a bin. For the same reason storage bins for pulverised coal should never be placed in close proximity to furnaces, boilers, steam-pipes or flues.

Whenever a plant is to be shut down for a few days all storage bins should, if possible, be emptied of coal. Where it is not possible to empty the bins they should be thoroughly inspected for hot coal, before the plant is again put in operation.

In the circulating system of using pulverised coal the primary air

pressure should always be maintained at a much higher pressure than that of the secondary air.

If a coal-circulating line becomes plugged up the furnaces should be immediately cut out and the secondary air stopped.

After the line has been cleaned it is essential that no smouldering particles of coal be left in the line, and before starting the fan a thorough examination of the line should be made.

Burners should be frequently inspected and any coke formed thereon should be removed.

Circulating lines should be blown clean of coal when shutting down at the end of the day's work.

The mixture of air and coal in the furnace should never be ignited by reaching in or opening the doors.

All conveyors and elevators should be tightly enclosed and should never be opened while running. Before opening, the machinery should be stopped and the dust allowed to settle.

A coal line, compressed-air tank or storage bin should never be opened in the vicinity of a flame or open light.

All electric wires and cables should, as far as possible, be enclosed in conduits.

All switches should be placed outside the pulverising plant, or placed in dust-proof casings.

Non-sparking motors or motors in dust-proof housings should be used in the pulverising plant.

Precautions should be taken against sparks from static electricity in all rapidly moving machinery by having it thoroughly guarded.

All electric-light bulbs should be kept from accumulations of dust, and all portable lights should have the bulbs protected by heavy wire guards; care should be taken to prevent arcing from loose socket connexions or imperfectly insulated cords.

All leaks in pulverised coal circulating lines or storage bins should be stopped as promptly as a leak in a gas line.

All the men should be educated to the dangers of coal-dust.

Light, cleanliness, and especially the education of the staff who work

in the installation, are the most important points. According to American documents, the whole of the accidents in powdered fuel plants from 1896 to 1920 have not caused more than thirty deaths ; and most of these have occurred during trials or experiments. Of the rest nearly all were due to causes which should not have occurred, and which, had a little thought, ordinary care and common-sense been exercised, would not have occurred. As Mr W. Greenwood said, in the discussion on Mr Tracy's paper : "The fact that powdered coal is not as liable to ignition as gas under ordinary methods of handling has disarmed caution, and this has been responsible for nearly all the serious accidents that have ever occurred when pulverising or handling it. All the principles involved in igniting it where damage can result are well known, but the failure to ignite on many occasions when conditions are nearly similar to what they are when ignition will occur develops the belief that the ripe conditions are not likely to be present, and this aids in disarming caution." If for the mental attitude here described there can be substituted one of alertness based on the knowledge that is suggested, the risk of fire or explosion will practically disappear.

Blizard, p. 110, summarises the advantages of pulverised fuel firing as follows :—

"A modern, well-designed multiple-unit powdered coal fired boiler plant is operated more easily than a modern stoker plant, for the following reasons :—

"(*a*) There is but little coal in the furnace at any time, which makes it possible to increase or decrease the rate of combustion very quickly by changing the rate of supply of coal and air.

"(*b*) Practically any coal may be burned completely with a small excess of air, and without making any but the simplest changes in feeding the coal and air.

"(*c*) No mechanism is exposed to the high furnace temperature, and the costs of installation, maintenance and operation of the boiler-firing machinery will be less than in a stoker plant.

"(*d*) Very little labour is required to operate the boilers. One man can operate five large boilers, and he has none of the arduous work involved in caring for the fire-bed of a stoker.

"(*e*) The ash, if the furnace be properly designed, gives less trouble and costs less to remove than the ash in stoker plants.

"(*f*) The powdered coal fired furnace is quickly and simply adapted for burning gaseous or liquid fuels should they be available at a cheap price.

"(*g*) In everyday running the efficiency will be higher than with stoker fired boilers, because of the smaller loss due to unburnt fuel and the smaller loss due to using less air to burn the coal.

"The above advantages are offset by the first costs, maintenance and operation of the preparation plant machinery for a powdered coal plant. The operating expense of the distribution system will vary with the system used and plan of the plant, but with good design need not exceed the costs of distributing the coal in a stoker plant, and may be less."

But it would be foolish to pretend that everywhere, and in all circumstances, it would be wholly advantageous and profitable to uproot an existing installation and substitute for it one burning fuel in the powdered form. Muhlfeld, in the very thoughtful paper so often quoted, says that: "Decision regarding the substitution of powdered fuel for any other fuel should be reserved until a careful, unbiased, expert analysis has been made of the comparative costs. This analysis should include installation, interest, depreciation, taxes, insurance, operating and upkeep expenses, from the source of fuel supply to the stack. And no system of powdered fuel drying, milling, storage, distribution, feeding, or burning should be considered for a permanent installation unless it provides for the prime necessities of proper fuel preparation and handling, correct firing and furnace design, and satisfactory operation; and unless it has demonstrated, in actual operation, its adaptability, practicability, safety, efficiency and economy with the fuel to be used, for the kind of service required.

"In general, the factors justifying the serious consideration of the use of powdered coal may be stated to be:

"1. Daily consumption of 80 tons or more of average commercial coal or other solid fuel equivalent, from one preparation plant.

"2. Need for greater output from existing equipment.

"3. Available supply of cheap low-grade fuel.

"4. Special operating requirements, such as irregular and peak loads; exacting character (neutral, oxidising or reducing), length, or direction of flame ; excessive banking and stand-by periods.

"5. Advisability of reducing the human element factor, particularly as relating to arduous non-productive labour.

"6. Desirability of minimising fuel and labour, both of which are expensive.

"7. Expensive ash-handling, and boiler and furnace upkeep.

"8. Need for reduction of smoke, soot, sparks and cinders.

"9. Available gaseous liquid or solid fuels for use in the same furnaces in combination or independently."

POSSIBILITIES

The use of powdered coal for domestic purposes and for similar small users has been attempted, the coal being powdered at a central station and transmitted in small containers to the consumer ; but as far as the author is aware no developments have taken place in this direction, even where central heating is in vogue. The need for plant and power to supply air to the burner is probably a sufficient reason to account for this.

Attempts have been made to gasify coal in the powdered form in a producer. It seems at first sight as though the reactions between coal and air, or coal and air and steam, might be carried on with greater uniformity, and with better regulation and control, under circumstances where intimate mixture could be secured than where the gaseous reagents have to find their way through the irregular interstices in a bed of fuel; and that an economy of space could also be effected through the more rapid reaction that we could expect. There would, however, probably be greater difficulties with ash than in ordinary producer practice: the finely divided ash would be carried forward in the gas in much greater quantity, and the difficulty and cost of cleaning the gas would be increased ; whilst for purposes for which clean gas was not needed the direct combustion of the powdered coal would be much more economical. Sinnatt and Slater have published (*Fuel*, 1922, p. 2) some figures which are

of interest in connexion with this subject. They find that powdered coal suddenly heated to 530° C. or above clots into spherules very considerably larger than the original particles—coal originally passing a 200-mesh sieve was after this treatment largely retained on a 90-mesh sieve and some of the clotted spherules were retained even by a 10-mesh sieve; but if the same coal was first heated only to 420°-500° C., which was done by a fall of 18 to 12 seconds through space at that temperature, it lost its caking powder, and did not clot when subsequently heated to the higher temperature.

The use of powdered coal in internal combustion engines has been frequently suggested; but whilst the suggestion is one that deserves consideration, and is not to be hastily dismissed as necessarily impracticable, the difficulties in the way are without doubt very considerable. It is by no means clear that the complete combustion of the mixture of powdered coal and air could be effected with certainty in the very short time available—for the "fineness" or intimacy of the mixture is far below that of a mixture of gas or vapour and air, and probably below that of the mixture of oil and air in a Diesel engine. And the ash of the coal would be a serious hindrance. At the high temperature of the explosion and in the confined space of the cylinder the ash would fuse and probably clot, so that a large proportion of it, instead of being carried out with the waste gases, would remain in the cylinder to clog the piston and wear the metal. Prof. Gerald Stoney, during the discussion on a paper by the author on powdered fuel, suggested that the effect of ash here would be no greater than that of the dust taken into the cylinder of a motor car engine with the explosion air, pointing out that from 20 to 30 lbs. of air, say 330 to 400 cubic feet, were taken in with every lb. of petrol burnt; but 2 lbs. of coal, using approximately the same quantity of air, containing as little as 6 per cent. of ash, would furnish approximately 2 oz. of ash, or about $2\frac{2}{3}$ grains for every cubic foot of air.

PART II

COLLOIDAL FUEL

THIS name has been given to mixtures of fuel oil with finely divided coal or other solid combustible.

From the time when oil was first successfully used as an industrial fuel, the advantages, in point of storage, transport, and "stoking," of a fuel which could be delivered to the burner through pipes and be atomised for its ready combustion, have forced themselves upon the attention of inventors ; and the possibility of reducing coal or other solid fuel to such a condition, by powdering it and mixing it with oil, has often presented itself.

The outstanding difficulty, however, with such mixtures has been to render them stable or permanent and to prevent the separation by subsidence of the particles of the solid fuel, always of higher specific gravity than the associated liquid. Such a separation not only produces inequalities in the composition of different portions of the fuel, but would lead to stoppages in pipes and valves, and consequent disorganisation of the whole plant.

Imagine some fine sand to be stirred up in water, and to be kept agitated by some means so that the sand remains uniformly distributed. In common language, the sand is said to be suspended in the water, and the system would be spoken of as a suspension of sand in water. In modern chemical language such a system would be called a disperse system of two phases—the water being one phase, the sand the other. Obviously, we can pass from any one point in the water to any other point without contact with any of the sand particles ; but we cannot pass from one sand particle to another without passing through an intervening space of water. This is expressed by calling the water the continuous phase, and the sand the disperse phase.

Consider now a similar system, in which the sand is substituted by a similar quantity of equally fine common salt. Initially, the two systems

will be exactly similar ; but very shortly the salt will have disappeared, having been, as we say, dissolved by the water. The system will now appear to the eye to be uniform and homogeneous ; though if we try to make a mental picture of the actual condition of things it will be difficult to resist the idea that it is still a two-phase disperse system, consisting of a disperse phase of salt particles of molecular fineness in a continuous phase of water.

Let the agitation now cease. Soon the sand will have settled to the bottom, leaving pure water above ; but however long we leave the other system, analysis will show that the salt does not settle out, but remains evenly distributed, a given volume from the surface containing exactly as much salt as an equal volume from the bottom.

The term colloid is due to Thomas Graham, who, shortly after 1860, discovered that when certain substances were dissolved in water and placed in a vessel closed at the bottom by a vegetable membrane like parchment paper, and the vessel was suspended in an outer vessel of water so that the levels of the liquids in the two vessels were the same, they diffused through the membrane into the outer water ; and if the outer water was renewed at intervals were ultimately removed from the inner vessel. Certain other substances, treated in the same way, were unable to pass through the membrane, but remained unchanged in the inner vessel. Substances in the first class, such as common salt, sugar, nitre, Graham called crystalloids ; those in the second class, like gum arabic, albumin, gelatin, he called colloids, from their resemblance to glue. The process itself he called dialysis.

More recent research has shown that there are not two classes of substances differing in nature in such a way that the members of one class form colloidal solutions, or sols, as they are now called—that is to say, apparently clear and homogeneous solutions, but of such a nature that they undergo no change if we submit them to dialysis—while those of the other do not ; but that practically all substances can be obtained, by appropriate means, in the colloidal form.

It is of interest, from the point of view of " colloidal fuel," to learn in what respects a colloidal solution differs from a true solution of a given

substance, and to become acquainted with two or three properties of colloids.

If solutions of copper sulphate and potassium ferrocyanide be mixed, copper ferrocyanide and potassium sulphate are formed by exchange, and the copper ferrocyanide, insoluble in water, forms a precipitate which settles to the bottom of the vessel. If, however, the solutions be dilute, each containing not more than 0·75 gram of its dissolved solid per litre, there is no precipitation, but a clear, red-brown liquid is formed. If we pour this upon a filter of ordinary filter paper it goes through as a whole, and it would appear from this that the potassium sulphate and the copper ferrocyanide are both dissolved ; but if we dialyse the liquid we find that the potassium sulphate alone diffuses through the membrane, and that the copper ferrocyanide remains in the inner vessel, as a colloidal solution, or sol.

A very probable reason for the differing behaviour of true solutions and of sols towards filter paper and parchment paper at once suggests itself—namely, that the pores of the filter paper are large enough to allow the passage of the separate particles of the substance in either case, whilst those of the parchment paper are much smaller ; and that the particles in the sol too large to pass the pores of the parchment paper must be molecular aggregates very much larger than the molecular aggregates or possibly single molecules in the true solution. This is not the whole explanation ; but it is in fact a part of the explanation, and it has been found that the diameters of the pores in parchment paper and other dialysing septa run from about 20 to 1000 millionths of a millimetre, which therefore must be approximately the minimal dimensions of the particles in the sol.

A sol, or suspensoid (a sol, the disperse phase of which is a solid, is so called : if the disperse phase be a liquid the sol is called an emulsoid), then, is intermediate between a suspension and a true solution. They differ from one another in the size of the particles of the disperse phase ; and if so, there will presumably be no clean and definite breaks or intervals between suspension and suspensoid, suspensoid and solution, but the one will merge gradually into the next, through " border " instances which it will be difficult to classify.

One character the suspensoid and the solution have in common: the particles of the disperse phase remain permanently in uniform distribution in them, and do not settle out as they do from the suspension. The reason for this is to be found in surface actions. Where two substances have a common surface of contact there are always forces between them (of what origin or nature we need not here inquire) acting at that surface; and the more the surface is increased for a given mass of substance the greater will these forces become in comparison with the weight of the substance or any other property depending on its mass. Now the increase of surface with subdivision of a substance has already (p. 18) been pointed out. A cube of 1 cm. in the side has a surface of 6 sq. cm.; but if this be divided into particles of $\frac{1}{10,000}$ the linear dimension (*i.e.* one thousandth or 1000 millionths of a millimetre, the size of the largest pores in the dialysing medium), the aggregate surface of these particles will be 10,000 times 6 sq. cm., or 6 square metres. The surface energies acting on the substance now, therefore, will be 10,000 times as great as they were on the centimetre cube, and may well be sufficient to neutralise altogether the effect of gravity on the individual particles.

Two more properties of suspensoids. If to the copper ferrocyanide sol referred to above we add a few drops of a solution of common salt or almost any other electrolyte, the sol becomes turbid, and after some time the whole of the copper ferrocyanide sinks to the bottom as a flocculent precipitate, leaving a colourless liquid above it. This flocculation by electrolytes, and consequent instability, is a common property of suspensoids, and is obviously due to the coalescence of the particles of the disperse phase into larger aggregates, beyond the colloidal size.

But this effect of electrolytes can be in many cases lessened or neutralised, and the stability of the suspensoid greatly increased, by the addition of a small quantity of another colloid, usually of an emulsoid character, known because of its effect as a "protective colloid." Sols of gelatine, casein, gum arabic and dextrin, for example, behave in this way, and very small amounts of them—in some instances as little as 1 part in 2000—are sufficient to afford protection, or to stabilise the suspensoid. It is not unreasonable to suppose that whatever may be the cause of this

protective action, these protective colloids will tend to exert a similar effect even on the larger particles of suspensions, though perhaps the result of the tendency may not there be very obvious.

In the case of suspensions, the disperse phase will always settle out if the system be left at rest; but the rate at which subsidence takes place will depend upon the nature and the circumstances of the individual suspension. Stokes, in 1850, showed that if a large sphere sinks in a liquid, it soon, since the resistance of the liquid to its fall increases as it gains speed, reaches a constant or steady speed, which is given by the formula

$$V = \frac{2r^2(s - s^1)g}{9v}$$

where r is the radius of the sphere, s and s^1 are the specific gravities of the sphere and of the liquid, and v is the viscosity of the liquid in absolute units. The formula expresses the fact that the speed of sinking will be smaller the greater the viscosity of the liquid and the less the difference in specific gravity between the sphere and the liquid; and since it is proportional to the square of the radius, it will diminish very rapidly as the sphere is made smaller—a sphere whose radius is one-tenth of that of another sphere will sink at only one-hundredth of the rate at which the larger sphere will sink. Thus if we calculate from Stokes's formula the rate of sinking, in oil having a specific gravity of 0·900 and an absolute viscosity of 6, of a sphere of coal having a specific gravity of 1·467, 1 cm. in radius, we find it to be 18·5 cm. per second; but spheres of the same coal which would just pass through sieves having 20, 40, 60 and 80 meshes to the cm. (assuming in each case the actual aperture to be half the nominal mesh, the other half being taken up by the material of the network) would attain speeds of 240, 60, 15 and 3·75 cm. per day. Apart, therefore, from any question of surface actions and the colloidal state, it is clear that approach to stability and permanence, in a mixture of coal and oil, will be made by grinding the coal very fine and choosing an oil of considerable viscosity.

One of the earliest attempts to produce a "colloidal fuel" was made by Plauson, of St Petersburg, in 1913. His plan was to reduce the size of the particles of coal to actual colloidal dimensions. In his English

patent (17729) of that year he states that no attempt has yet been made to convert coal or wood charcoal into the colloidal form, and that his invention has for its object a method of employing such colloidal coal or charcoal for heating. He suggests that one great advantage would be that the coal could be used directly in internal combustion engines. His method of treatment is to grind the coal in the first place till it will pass a sieve with 80 meshes to the cm. or 200 to the inch; and then to mix this fine powder with water or a liquid hydrocarbon, and grind it further between polished plates running at a high speed or under a pressure of 60 to 100 atmospheres. The substance so produced presents all the properties of colloidal solutions or emulsions. The process may be accelerated by adding from 1 to 3 per cent. of a "protective colloid" such as soap, milk, gelatine or albumen to the water, or soap solution, india-rubber, etc., to the liquid hydrocarbon. And the disintegration need not always be carried as far as the truly colloid condition; the production of an emulsion may often be sufficient.

Plauson's proposals do not seem to have attracted much notice, or at least to have been regarded with much favour; and indeed the cost and difficulty of the extremely fine grinding which he contemplated would seem prohibitive for the production of a fuel for industrial use.

The more recent researches which led to the development of so-called "colloidal fuels" were the result of the stimulation of inventiveness produced by the hard necessities of the war. In 1917 the German submarine menace was threatening the allied nations in many ways, and a combination of about a hundred large American and other shipping, insurance, oil and mercantile companies and firms combined to form the "Submarine Defence Association" to devise means of countering the attack. Mr Lindon W. Bates was made Chairman of the Engineering Committee, and had charge of the technical side of the Association's work; and Admiral Benson, Chief of the American Naval Operations, made over to the Association the U.S.S. *Gem*, a small vessel with Normand destroyer boilers, for experimental work.

Many and varied problems faced the Association, but very early the question of the conservation of oil fuel became urgent, through the German

efforts to interrupt its transport. A substitute for oil fuel, or at least an auxiliary that would lessen the amount of oil fuel needed for naval purposes, was urgently needed. At the request of the British Admiralty the Association examined into the possibility of feeding the furnaces of naval vessels with powdered coal. Experiment showed that it could be used at sea as successfully as on land, but as the installation of pulverising machinery was not practicable on board ship, and as the space needed for storage of the fuel was at least twice as great as that for oil of equal calorific effect, the steaming radius of vessels using it would have been too greatly reduced. Experiments were therefore instituted on the mixture of coal with oil, a subject which had at a much earlier date occupied Mr Bates; and the Kodak Research Laboratory, with some of its staff, Dr Sheppard, Mr Capstaff and Mr Eberin, who were already interested in the problem, were, through the courtesy of its Directors, placed at the disposal of the Association. Experimental work very shortly produced in the laboratory a mixed oil and powdered coal fuel which was stable over very considerable periods of time, and the technical development of this was so successful that the *Gem* was worked from April to July 1918 solely on this fuel with results satisfactory in every respect.

In the first experiments a semi-anthracite coal of sp. gr. 1·467, pulverised so as to pass a sieve of 40 and be retained on one of 80 meshes to the cm., was mixed with an oil of sp. gr. 0·900 and absolute viscosity 6 (corresponding to a flow of 50 c.c. from Redwood's viscometer in about 2800 seconds), so that the coal formed about 30 per cent. of the whole by weight. The settlement, which by Stokes's formula should have taken place at between 15 and 60 cm. per day, was very much slower, only becoming appreciable after about four weeks. Stokes's law is concerned with a single sphere in a liquid of indefinite extent: clearly a sphere beaten out to the form of a flat plate would sink much more slowly, and perhaps not in a vertical direction; and numbers of coal particles of varied shapes, in a very limited space of liquid, would certainly interfere with one another's descent. Possibly, too, the surface actions which we have been considering also came into operation to some extent, so that the deviation from Stokes's law is not difficult to explain. But though settlement

was satisfactorily slower than Stokes's formula would have suggested, it occurred; and experiments with less viscous oils showed that with them it was more serious. Further, as the fuel before atomisation in the burner required preheating, and the viscosity of all mineral oils falls very rapidly with rise of temperature, it was necessary to take this into account, and provide a fuel which should not only remain stable at ordinary temperatures for long periods of storage, but should also remain stable at higher temperatures during the comparatively short period of its flow through the firing system to the nozzle of the burner.

The chief method by which this was accomplished was by adding to the mixed fuel a "fixateur," which acted like a protective colloid. The "fixateur" or stabiliser which was found of most general use was a lime-rosin soap or grease.

This was made by suspending 5 parts of slaked lime in 83·5 parts of Texas navy oil, adding 1·5 parts of water and 10 parts of rosin, and heating until the rosin was saponified. The amount of fixateur needed depends upon the nature of the oil and of the coal; but usually the amount is such that the final product contains from 0·5 to 1·5 per cent. of rosin. The rosin may be substituted by balsams, turpentines, or other resinous by-products, or by pinewood pitch; and other alkalis may replace the lime.

The first fuels made consisted of about 30 per cent. of coal and 70 per cent. of oil. The coal was pulverised, as though to be used as such: about 95 per cent. passing through a sieve of 40 meshes to the cm. (100 to the inch) and 85 per cent. through one of 80 to the cm. (200 to the inch). The oil and the requisite amount of "fixateur" were measured out, and mixed with the coal in a ball-, tube-, or paint-mill. These fuels showed no sensible subsidence over a period of three months.

Another method of producing stability is the use of a "peptising" liquid—that is, one which has the opposite tendency to an electrolyte, and instead of favouring the flocculation of the particles of the disperse phase into larger aggregates, tends to disperse them still further, reducing them to smaller particles in greater number. Such "peptisers" are found in many coal-tar products, such as creosote oil, naphthalene, solvent naphtha,

or green anthracene oil. These may be used, in quantity amounting to from 5 to 20 per cent. of the total fuel, either at the ordinary temperature or at a temperature of 65° to 95° C., at which temperature the effect is usually greater, as is indicated by an increase in the viscosity, and by the greater number of particles in the mixture which are small enough to show the "Brownian movement" when examined under the microscope.

A third method, but one having several disadvantages, is to oppose the sinking of the disperse phase of coal particles by introducing similar particles of a "filler" of lower specific gravity than the oil, such as the waste from starch or flour mills, wood-dust, finely divided peat or lignite. These particles will tend to rise slowly through the oil, and will interfere with and more or less nearly neutralise the downward tendency of the coal particles.

Any kind of pulverisable carbonaceous material may be used in making colloidal fuel: Bates in his principal patent claims the use of anthracite, semi-anthracite, bituminous and semi-bituminous coals, lignites, peats, anthracite culm, dust and slush, bituminous and lignite slack, screenings and dust, coal-seam dust, pressure-still coke, furnace or foundry coke, gas-coke, charcoal and wood. Obviously the calorific value of the fuel will depend on that of the powder: where it is important to store a maximum amount of energy in minimum space, a fuel must be chosen as free from ash and moisture and as high in calorific value as possible; but where concentration is not important, and where low-grade coal presents itself as the only possible fuel, or as one which it is desirable to utilise, the production of colloidal fuel affords an opportunity for using it efficiently.

Further, the specific gravity of the solid is a factor of importance. On the one hand, high specific gravity (if it be that of the combustible substance itself) means high calorific value per unit volume, but, on the other, it means high speed of sinking for particles of a given size, and consequent difficulty in stabilising. It is important to remember this aspect of the case in considering low-grade fuels high in ash, which through the ash have high specific gravity.

The final product should be denser than water; hence the coal should

form at least 10 per cent., and even up to 40 per cent., of the whole. The amounts and kinds of the ingredients should be selected with the specific gravity, the stability and the calorific value (per unit volume) of the fuel in view.

The liquid used is of course usually fuel oil; but other substances may be used, such as pressure-still oil or tar, coal-tar, molasses, and even hydrocarbons ordinarily solid, if used at temperatures above their melting-points. The two most important physical characteristics of oils for the purpose of colloidal fuel are specific gravity and viscosity. The range of specific gravity among the oils which can be practicably used is not very wide; but clearly high specific gravity, other things being equal, is an advantage, from the point of view of the stability of the composite fuel. The range of viscosity among these oils, on the other hand, is enormous; and whilst a viscous oil, as indicated by Stokes's formula, is advantageous, as lowering the speed of a particle sinking through it and so contributing to the stability of the colloidal fuel composite, yet, from the points of view of the mixing operation and of the flow of the fuel through pipes and its atomisation in burners, high viscosity is objectionable.

Fortunately, in this regard, the viscosity of all mineral oils falls off very rapidly with rise of temperature; and an oil may be obtained, viscous enough at the ordinary temperature to make readily a stable composite, and mobile enough at a higher temperature quite practicable to attain to flow readily and atomise completely. At the low temperature it is stable enough for storage, and it is not kept long enough at the high temperature for any sensible separation to occur. Such higher temperatures must, of course, be below the flash-point of the oil; but as all ordinary fuel oils flash above 150° F. (65° C.)—the British Admiralty specifies a minimum flash-point of 175° F. (80° C.)—this requirement can be easily met. Experience has shown that an oil for use in making colloidal fuel should preferably have a viscosity at 20° C. of 20° E (600 seconds Redwood) and at 30° C. of 10° E. (300 seconds Redwood). Where a number of different oils are available having different viscosity-temperature curves, it is possible by blending them appropriately to produce an oil approximating in viscosity to any desired curve. But short of that,

viscosity may be increased by the addition of petroleum or asphaltic petroleum residues or heavy oils, or decreased by adding kerosene, turpentine, pressure-still oil, or other " cut back " of low viscosity. The emulsification of the oil by the addition of the fixateur of lime-rosin soap also tends to increase the viscosity of the composite, although it is not simply by increasing viscosity that the fixateur exerts its stabilising influence.

The experiments on the " peptising " effect of creosote and other coal-tar products indicated the possibility of effecting the stable mixture of coal-tar with petroleum oil by means of pulverised coal. (Pickering had long ago shown that a finely divided solid could effect the blending or emulsification of two immiscible liquids.) The attempt was successful, and coal-tar and its products are now available as adjuncts to petroleum in the production of this class of fuel. For example, a stable fuel can be made by mixing 50 per cent. of residual oil from pressure stills, 20 per cent. of coke-oven tar and 30 per cent. of pulverised coal. With Texas oil, more coal in proportion to tar, and more oil in proportion to both tar and coal, must be used.

Later experience has shown that it is preferable to grind the coal in oil. This promotes intimate mixture better than blending after pulverisation, and it also results in finer grinding, and thus raises the stability of the product. It is found that the grinding is more efficient as the viscosity of the oil is lower, and hence it is preferable to grind the materials hot rather than cold. Further, the lower the viscosity of the oil, the smaller the proportion that need be used in grinding the mixture. The best mixtures (for grinding) contain from 35 to 65 per cent. of oil, according to its viscosity. Good results are obtained by grinding two or more different varieties of carbonaceous material with oil or with more than one liquid. The duration of the grinding varies with the materials and with the type of mill used. Almost any of the ordinary coal-pulverising mills may be used, such as the Fuller, Harding, Smidth or Raymond, though some of these need modification or mechanical adjustment when the coal is ground with oil.

For example, the following results were obtained with a Smidth

" cylpeb " mill working at a speed of 40 to 42 revolutions per minute per 200 lbs. of " cylpebs " : 1. Anthracite coal 20 lbs., water-gas tar, viscosity 37·6° E. or 1170 seconds Redwood at 70° F. (20° C.), 2° E. or 64 seconds Redwood at 200° F. (93° C.), 37·2 lbs., initial temperature 200° F., coal reduced from 15·8 to 88·6 per cent. through 200-mesh in 15 minutes. 2. Mexican oil of specific gravity 0·948 substituted for the water-gas tar: 89·3 per cent. of the coal passed 200-mesh in 20 minutes. 3. The same Mexican oil, but working throughout at ordinary temperature: 89 per cent. of the coal through 200-mesh in 70 minutes. With this mill and the same coal the grinding efficiencies (lbs. of coal ground to 85 per cent. through 200-mesh, per hour per lb. of grinding elements) for different liquids were: cold Mexican oil 65 per cent., 0·09; hot oil 65 per cent., 0·325; hot Mexican oil 50 per cent. and water-gas tar 15 per cent., 0·37; hot water-gas tar 65 per cent., 0·417; Pennsylvania oil (viscosity about that of kerosene) 35 per cent., 0·8.

All the oil needed for the fuel may be added in the mill; but it may sometimes be preferable to use in the mill a smaller quantity, and in that case the remainder must be added in a separate mixing vessel after grinding is finished. Usually the oil so added, if not the same as that used in the mill, should have at least as high a viscosity as that oil. The blending with the additional oil, like the grinding, may be done at a high temperature; and when heat is used in those processes, the longer it is applied, within reasonable limits, the better, as helping towards more intimate mixture and thus towards stability. For this purpose a temperature between 65° and 95° C. will usually be suitable.

The fixateur may be added in the mill or, if more oil is to be added later, in the blending operation. Its uniform diffusion throughout the fuel must, in either case, be secured.

Two typical fuels are as follows:—1. Anthracite coal 15 per cent., bituminous coal 15 per cent., water-gas tar 15 per cent., fuel oil 55 per cent. The coals are ground with the water-gas tar and 20 of the 55 parts of fuel oil, in a Smidth mill, starting at a temperature of 95° C., attained either by a steam jacket around the mill or by heated cylpebs, for about twenty minutes. The resulting paste is transferred to a mixing vessel,

where the remaining oil is added, and the mixture stirred for about forty minutes, whilst its temperature is kept up by a steam coil. The product will remain stable for more than a month. 2. Dehydrated lignite 35 per cent., mineral oil 55 per cent., lime-rosin grease 10 per cent. (introducing 1 per cent. of rosin and 0·5 per cent. of lime). The lignite is ground with 45 of the 55 parts of oil, till 85 per cent. of it will pass 200-mesh, and

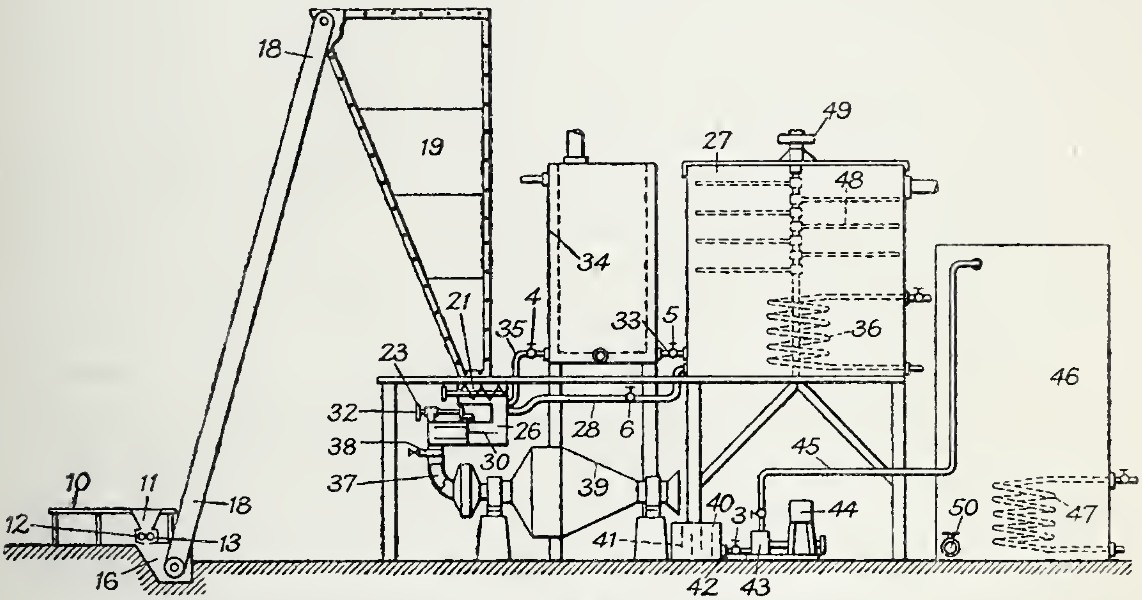

Fig. 53.—Diagram of Plant for Manufacture of Colloidal Fuel

the remaining oil and fixateur blended with the product in a separate vessel. Such a fuel will be stable over three months.

The description of the method of manufacture of these fuels indicates generally the nature of the plant required. The diagrammatic illustration, slightly altered from that given in one of Bates's patents, shows generally the arrangement of a suitable plant. The coal is dumped on to the platform at the left hand, whence it is shovelled or automatically fed into the crusher, and the crushed coal falls into the pit, from which the elevator delivers it into the large hopper. The screw conveyor at the bottom of the hopper delivers it at a regulable rate into the " pre-mixer " below, into which is led at the same time oil from the large tank, and the fixateur or other protective substance from the smaller tank. Communication between these tanks allows oil to be mixed with the fixateur,

if that be necessary, and the tanks may be provided, if necessary, with heating and agitating appliances. The pre-mixer is also furnished with an agitator, and the mixed substances pass from it into the mill below, where they are ground together to the requisite degree of fineness, and from the open end of which they fall into a small tank. Settlement of any large particles takes place in this tank, and the colloidal fuel is pumped from the small tank into the large storage tank on the extreme right, which is also provided with the means of heating the mixture, should that be necessary. Naturally, other forms of mill, and other arrangements of detail, will in many cases be equally applicable.

Mixtures can be made containing up to 45 per cent. of solid carbonaceous particles, which yet remain liquid; and even if the solid be increased up to 75 per cent. of the whole, the paste so produced is still atomisable.

The separation of ash from coal by froth flotation may be combined with the production of a colloidal fuel. In the processes of "Minerals Separation Ltd." the finely ground coal is agitated with water and a small amount of oil, and air is drawn into the mixture ; the coal particles attach themselves to the air and oil, forming a froth which floats on the surface and is removed, whilst the associated mineral matter sinks and is rejected. In this process as little oil as possible is used, for economy's sake ; but if the oil is to form part of the ultimate fuel, more may be used. It is indeed desirable to use more, for some of the oils used in froth flotation also act as peptisers, and others form with alkali a suitable soap for a stabiliser. The oil should exceed 1 per cent. of the carbonaceous material, and for peptising purposes more still is better ; say, for a fuel to contain 30 per cent. of coal, 3 per cent. of creosote and 2 per cent. of mineral oil.

The method of producing colloidal fuel with the aid of froth flotation is indicated in the diagrammatic sketch of plant which accompanies Bates's English Patent 160754, and which is reproduced with slight modification on page 189.

At the extreme left are seen the entries for coal, oil and fixateur, which are carried by the screw conveyor into the pulveriser *a*, which is jacketed so that it can be heated if need be. The pulverised mixture passes from

the other end of the mill into the agitating vessel *b*, where it is churned by the agitator, and where air is injected into it from the pipes below, passing through a canvas screen supported by wire-netting. Water enters this vessel from the top; some of the ash settles in the near portion of the vessel, and the froth with the rest of the ash goes into the spitzkasten section of the vessel, where the rest of the ash settles and can be removed from the bottom. The froth passes over a lip to the inclined launder *c*,

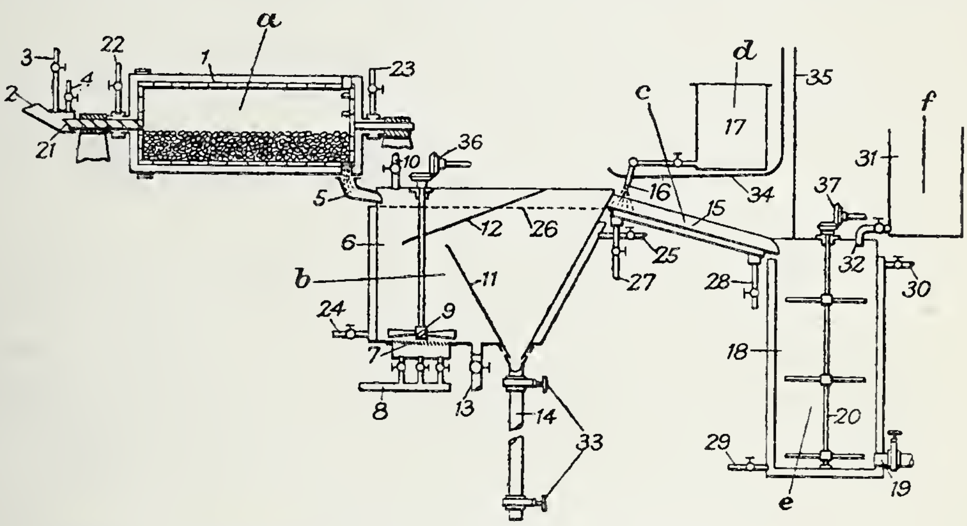

FIG. 54.—FROTH FLOTATION AND COLLOIDAL FUEL MANUFACTURE

which can be heated below. Oil from the tank *d* is fed upon the froth and kills it, and as the mixture passes down the launder much of the water it contains is evaporated, the steam passing off through a hood and pipe. The dried mixture falls into the mixing vessel *e* (jacketed and heated if necessary), where it is mixed by the agitator with the required amount of additional oil from the tank *f*. The finished product is drawn off from *e* as required.

The conditions for the use of colloidal fuel are practically those for the use of oil fuel. In the experimental work of the *Gem* the fuel was stored in the oil tanks and used through the oil burners. The following report was given of the working :—

Equipment.—No changes in the standard navy Schutte & Koerting mechanical burners were made. Changes in the pumping and furnace were as follows :—(*a*), an additional 2-inch pipe was run from the bottom of the

fuel storage tank to the oil pump suction, a distance of about 35 feet; (*b*), a reversing-flame combustion arch was installed at the rear of the boiler furnace.

Atomisation.—The temperature and pressure necessary to atomise the colloidal fuel properly corresponded closely with those necessary to atomise the base fuel oil. At approximately 150° F. and 150 lbs. pressure the atomisation of colloidal fuel was as good as that of the regular oil fuel.

Efficiency.—(*a*) *Capacity.*—With the same burners colloidal fuel generated about the same volume of steam as the regular oil fuel. (*b*) *Thermal Efficiency.*—The B.Th.U. consumption of colloidal fuel per indicated horse-power was approximately equal to that of the regular oil fuel. (*c*) *Smoke.*—Colloidal fuel produced no more smoke than regular oil fuel, neither causing practically any smoke.

Fluidity.—Due to higher viscosity than oil of the colloidal mixture at low temperatures the regular pump suction was doubled to get full pumping capacity. No changes were necessary in the pump discharge. At the temperature and pressure above noted the rate of flow of colloidal fuel through the burners was about that of fuel oil, according to data furnished by the Schutte & Koerting Company.

Wear on Burner-Tips.—Although a slight extra erosion of the burner or orifices might have been expected, no trouble was experienced from this cause during three months' intermittent operation. Wear in pumps, if it should occur, can be minimised by using larger pumps with slower piston travel.

Stability.—(*a*) *In Storage.*—Stored in the fuel tank at about 40° to 55° F., colloidal fuel required no mechanical agitation until after nearly three months. The slight settlings of what was then unused were easily stirred into the remaining fluid. (*b*) *In Pipe Lines.*—No troublesome settling occurred in the cold lines leading to the heater. None occurred either in the hot lines between the heater and the burners while the burners were delivering. Settling of coal did occur in the burner-tips when they were shut off longer than two or three minutes, unless first flushed out with regular fuel oil. In an installation depending entirely upon colloidal fuel the burners might be equipped with a steam connexion, so as to blow out the orifice whenever the flow of colloidal fuel was stopped.

General Operating Satisfaction.—After short instruction and experience the regular navy crew were able to operate the ship using colloidal fuel with quite as much confidence as with the regular oil.

General Conclusion.—Colloidal fuel can be utilised for marine steaming purposes under practically the same conditions and with as good results as with the navy oil. The saving of oil for equal weights of fuel was 31·2 per cent., but because of the lower heat value per lb. of colloidal fuel compared to oil, about 10 per cent. more of it, by weight, is needed to produce equal heat value. This means a saving, for equal heat value, of 27 per cent. of oil. For equal heat units the colloidal fuel has nearly 2 per cent. less volume than the oil with which it is made.

The advantages of colloidal fuel over solid fuel firing are in the main the same as those of oil or of pulverised coal firing: 1. Increased efficiency, caused by the more nearly complete combustion and lessened loss of combustible in the ash, and by the smaller amount of excess air needed for combustion. 2. The ease with which smokeless burning can be attained. 3. Flexibility of operation and power of rapid regulation, so that sudden demands or overloads can be met. 4. Lower grades of coal can be successfully and economically burnt. 5. Firing can be stopped at once, and can be started at once, so that steam can be got up very rapidly. 6. The labour required is greatly reduced in amount.

As compared with oil fuel, colloidal fuel is more concentrated, or contains more heat units in the same bulk, than oil, so that either space for fuel storage can be lessened by substituting colloidal fuel for oil, or the steaming radius can be correspondingly increased. Being denser than water, colloidal fuel sinks in water, and hence may be quenched by water if accidentally inflamed, or "fireproofed" by being kept under a seal of an inch or more of water. Small as the danger of explosion is in properly managed installations of pulverised fuel, it is of course still less in a colloidal fuel installation, as there is no dust-cloud in the fuel itself, nor can one be raised through accidental leakage of conveyor pipes or storage bins.

The following data and results of boiler trials are quoted from Mr

Lindon Bates as showing the working of the same boiler with two grades of colloidal fuel and with fuel oil. The colloidal fuels were composed as follows :—

	Grade 13	Grade 14
Coal	..	30·0
Coal (Pocahontas)	30·0	..
Coal-tar, etc.	..	12·0
Fixateur	1·5	1·2
Mexican reduced oil	28·8	..
Texas navy oil	8·5	6·8
Pressure-still oil	31·2	50·0

and yielded respectively 3·2 per cent. and 2·0 per cent. of ash. The oil was a Mexican reduced oil.

	Colloidal Fuel		Oil	
	Grade 13	Grade 14	Test 1	Test 2
Total heating surface, sq. ft.	4840	4840	4840	4840
Duration, hours	8	8	8	8
Steam pressure by gauge, lbs. per sq. in.	81·8	80·8	82·8	80·6
Temperature of feed water entering boiler, degs. Fahr.	79·3	111·4	109	106·7
Fuel per hour, lbs.	1286	1076	1146·5	1054·7
Equivalent evaporation per hour from and at 212° F., lbs.	17,846	15,942	17,202	16,567
Equivalent evaporation per sq. ft. of heating surface, lbs.	3·61	3·29	3·55	3·42
Rated capacity per hour from and at 212° F., b.h.p.	403	403	403	403
Percentage of rated capacity developed	126	115	122	118·8
Equivalent evaporation from and at 212° F. per lb. of combustible, lbs.	13·6	14·72	14·85	15·51
Calorific value of fuel, B.Th.U. per lb.	17,200	16,670	18,482	18,482
Efficiency of boiler, furnace and grate, per cent.	76·8	85·3	75·9	79·5

No figures from actual work seem to be available showing the cost of colloidal fuel. Mr Bates estimates the cost of manufacturing it, including the cost of fixateur, at $1\frac{1}{2}$ dollars per ton. He gives a comparison between colloidal fuel and oil, assuming that oil costs 6·89 cents and weighs 7·7 lbs. per gallon (hence 260 gallons per ton, and cost of \$17·91 per ton); that it is mixed with a hardened pitch of sp. gr. 1·3 costing \$5·00 per ton, the proportions being 65 of oil, 34 of pitch, 1 of fixateur; and that the calorific values of the oil and the pitch are respectively 19,000 and 16,000 B.Th.U. per lb. The colloidal fuel will weigh 9 lbs. per gallon (222 gallons per ton), and have a calorific value of 159,840 B.Th.U. per gallon. The cost per ton of the colloidal fuel will be:

Oil .	0·65×17·91=	\$11·6415
Pitch .	0·34× 5·00=	1·70
Manufacture and fixateur		1·50
		\$14·8415

A ton of oil gives 38,000,000 B.Th.U. for \$17·91, a ton of colloidal fuel 35,500,000 for \$14·84; hence the cost per million B.Th.U. is, for oil 47·1 cents, for colloidal fuel 41·8 cents. There is thus a saving on the side of colloidal fuel of 5·3 cents per million B.Th.U., or $11\frac{1}{4}$ per cent. of the cost of the oil.

Very little work seems to have been done, so far, in this country, on colloidal fuel; but a proposal which contemplates the possibility of running oil-burning installations on a fuel containing only 70 per cent. or less of oil, and of conserving the other 30 per cent., and which is said to effect at the same time a reduction in cost, certainly seems worthy of attention.

INDEX